This is to certify that the

dissertation entitled

Energy Efficiency and Grain Quality Characteristics of Cross-Flow and Concurrent-Flow Dryers

presented by

Juan Carlos Rodriguez

has been accepted towards fulfillment of the requirements for

Ph.D. degree in Ag. Eng. Technology

F.W. Bakker-Arkema

Major professor

Date 5/5/82

ENERGY EFFICIENCY AND GRAIN QUALITY CHARACTERISTICS OF CROSS-FLOW AND CONCURRENT-FLOW DRYERS

By

Juan Carlos Rodriguez

A DISSERTATION

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

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1982

ABSTRACT

ENERGY EFFICIENCY AND GRAIN QUALITY
CHARACTERISTICS OF CROSS-FLOW
AND CONCURRENT-FLOW DRYERS

By

Juan Carlos Rodriguez

An experimental and simulation study was conducted on the state-of-the art of US on-farm and off-farm corn drying technology. Experimental data was collected on four commercial cross-flow and one concurrent-flow dryers in four Midwestern states. Each of the dryers was analyzed in depth by simulation. Energy efficiency and grain quality were employed as the criteria for dryer evaluation.

Recirculation of exhaust air in cross-flow dryers was found to save as much as 30 percent of the required energy at a cost of about 10-15 percent on dryer capacity. Reversal of the direction of airflow in the drying section of a cross-flow dryer results in a significant decrease in the moisture content gradient of the outlet grain. Mixing the grain after partial drying in a cross-flow

dryer and tempering it before final drying/cooling, further decreases this moisture gradient.

The most sophisticated cross-flow dryer combines grain mixing and air recycling with an option to vary the velocity of the grain on the two sides of the individual drying/cooling columns. This design leads to energy efficiency and grain quality characteristics which rival those of multi-stage concurrent-flow dryers. The energy consumption of a differential grain speed cross-flow dryer (DGSCF) is less than 50 percent of that of a conventional non-recycling cross-flow model. The optimum grain speed ratio in a DGSCF dryer depends on the type of product, the initial product moisture content and the inlet air temperature; the speed ratio varies from 2:1 to 4:1 with the drying product closest to the air inlet flowing at the greater velocity. A further advantage of the DGSCF dryer is the shorter time at which the product is kept at high temperatures compared to other types of cross-flow dryers.

The multi-stage concurrent-flow dryer with counterflow cooler proved to be the best of the five dryers analyzed with respect to energy efficiency and grain quality characteristics. Due to the high inlet air temperatures of a concurrent-flow corn dryer (up to 550 F), the energy efficiency (even without air recycling) is as good that as of the DGSCF dryer. The grain quality characteristics are the best of any dryer tested; both the

Juan Carlos Rodriguez

grain breakage increase and the exit moisture content gradient approach zero.

Approved F. W. Bakker-Arkema
Major Professor 5/5/82

Approved Donald M. Edwards
Department Chairman 5/7/82

ACKNOWLEDGMENTS

I am deeply indebted to my guidance committee chairman, Dr. Fred W. Bakker-Arkema, who provided not only technical and moral support since 1979, but also friendship and examples that positively influenced my career and my way of life.

Special thanks is given to Dr. Robert Wilkinson and his wife, Ellen, not only for their service, but also for their friendship and spiritual and moral support.

I am also indebted to the other members of my guidance committee, Dr. Lawrence Copeland and Dr. Steve Harsh, for their assistance and friendship during this work.

Special thanks is given to the external examiners, Mr. Chris M. Westelaken, Dr. I.P. Schisler, and Mr. Steve Kalchik.

For their moral support, two fellow graduate students and their families deserve special mention: Eliud Ng'ang'a Mwaura and Carlos Fontana.

I am indebted to Pat Francek and Karen Dunn for their patience and help during the final writing of this work.

Special thanks and appreciation is sincerely expressed to the Andersons Agricultural Research Fund, Columbus, Ohio; Blount, Inc., Montgomery, Alabama; and Fundacion Banco Ganadero Argentino, Argentina for financial support. The author is also indebted to the Argentinian Government and the Instituto Nacional de Tecnologia Agropecuaria, Argentina for providing the opportunity to obtain this advance degree in Agricultural Engineering and for the financial support for this work.

The author is thankful to Mr. Dick Rastin and Mr. Ben Stevenson for their help during the experimental phase of this work.

A very special thanks is given to Don Duilio Moglianesi for his moral support and friendship.

I am indebted to the faculty, staff, and graduate and undergraduate students of the Department of Agricultural Engineering, at Michigan State University for their patience and friendship.

Deepest appreciation goes to my wife, Carlota, and my daughters, Carlota Veronica and Carola Viviana, for their patience and tolerance. A special note of praise should be given to my wife, whose expert typing helped to facilitate the completion of this doctorate thesis. To them, I can only offer myself and my love.

TABLE OF CONTENTS

Page

Page

LIST OF TABLES

Table		Page

Table		Page

Table | Page

Table | Page

LIST OF FIGURES

Figure		Page

LIST OF SYMBOLS

A	constant
a	specific product surface areas, ft^2/ft^3
B	constant
C_a	specific heat of air, BTU/lb F
C_p	specific heat of product, BTU/lb F
C_v	specific heat of vapor, BTU/lb F
C_w	specific heat of water, BTU/lb F
D	diffusion coefficient, ft^2/hr
F	degree farenheit
G_a	dry weight flow rate of air, lb/hr ft^2
G_p	dry weight flow rate of product, lb/hr ft^2
H	humidity ratio, lb/lb
HP	horsepower
h	convective heat transfer coefficient,BTU/hr ft^2 F
h_{fg}	heat of vaporization, BTU/lb
M	local or average moisture content, dry basis decimal
Me	equilibrium moisture content, dry basis (decimal)
Mo	moisture content at time t=o, dry basis (decimal)
Mt	moisture content at time t, dry basis (decimal)
r	kernel radial coordinate, ft
rh	relative humidity, decimal
ρ_p	dry weight product density, lb/ft^3
T	air temperature, F

t	time, hours
θ	product temperature, F
x	bed-depth coordinate, ft
y	bed-width coordinate, ft

CHAPTER 1

INTRODUCTION

In the last decade the world trade and consumption of feed grain has been rising steadily due mainly to the expansion of the beef, milk, and egg production. This is mainly attributed to a worldwide increasing demand of animal protein (Fernandez and Acuna, 1979).

Of all the feed grain, corn is the most important in volume, representing 19 percent of the total traded in 1978 (Fernandez and Acuna, 1979). The United States is ranked number one in corn exports, with 73 percent of the world market (Table 1).

A significant reduction in postharvest losses in shelled cereal grains have been achieved by the widespred use of artificial grain drying. By rapidly lowering the harvest moisture content and maintaining it at a specified level, grain retains its storage quality through reduced senescent metabolism and increased resistance to fungal and insect infestations (Brooker et al., 1974). A large variety of grain dryers are commercially available, with the cross-flow dryer the most widely used in North America (Gustafson and Morey, 1981).

TABLE 1: World export of corn, major countries in 1978.

COUNTRY	BUSHELS in 1,000	PERCENT
United States	1,967,979	73.24
Argentina	235,086	8.75
South Africa	109,961	4.10
France	99,079	3.69
Thailand	68,339	2.58
Brazil	550	0.01
Others	205,032	7.63
TOTAL	2,686,026	100.00

Source: Secretaria de Agricultura y Ganaderia de la Nacion, Junta Nacional de Granos. Publicacion No.70.

Corn is harvested when the moisture content is 20-35 percent wet basis. The final moisture content from the drying operation is determined by the intended use of the grain, and whether short or long term storage is planned. Continuous-flow dryers utilize high air-temperatures and flow rates, and high grain flow rates in order to achieve a satisfactory final moisture content (Brooker et al., 1978; Paulsen and Thompson, 1973; Holtman and Zachariah,1969).

Until recently dryers were evaluated mainly by total drying capacity. However, due to rising fuel costs, dryer efficiency must likewise be considered. Bakker-Arkema et al. (1978) suggested a standardized rating to be established for both dryer capacity and energy efficiency. Energy efficiency is improved by carefully compromising between air temperature and flow rates, grain column thickness and length, and grain flow rate (Brooker et al., 1978).

Computer models which simulate dryer performance have greatly aided both the design and evaluation of drying systems. The models are based upon mathematical equations which calculate the diffusion rate of moisture through the grain as a function of: 1) original moisture content, temperature, and physiology of the grain; 2) the relative humidity, temperature, and flow rate of the air; and 3) the configuration of the particular dryer (Shove and Olver, 1967).

1.1 Units

Throughout this thesis English units are used. The main reason of this decision is based on the fact that the research carried out was paid by grants from the industry. These private companies asked to make the reports to them in English units. Hence, a conversion to SI units for this thesis was not made because it would be counter productive. Appendix C presents conversion factors from English to SI units.

CHAPTER 2

OBJECTIVES

The objectives of this study are:

A. to evaluate the energy efficiency and grain quality of the following cross-flow dryers:

a. an on-farm cross-flow batch dryer;

b. an on-farm continuous flow cross-flow dryer with cooling air recirculation, and air reversal;

c. an elevator type continuous flow cross-flow dryer with heating and cooling air recirculation and with air reveral;

d. an elevator type/on-farm continuous flow cross-flow dryer with heating and cooling air recirculation, with tempering, and differential column grain velocity-flow;

B. to model and exhaustively compare the four basic cross-flow dryer configurations;

C. to evaluate the energy efficiency and grain quality characteristics of a three-stage concurrent-flow grain dryer; and

D. to compare the four cross-flow dryers with the concurrent-flow dryer.

CHAPTER 3

CORN IN ARGENTINA

The Argentine Republic occupies the southeastern portion of South America. It is 2,300 miles from north to south and 930 miles at its widest point. The country has a land mass of 1,072,750 square miles. It is the second largest Latin American Republic and is roughly one third the size of the United States.

Argentina has a population of about 27,210,000 inhabitants, with the lowest growth rate in Latin America of 1.8 percent per year. Population density as given by The World Almanac and Book of Facts (1981), is also quite low at 24.62 inhabitants per square mile as compared to a density of 61.19 per square mile in the United States.

Argentina has produced and exported grain for almost a century. The main crops are: wheat, corn, sorghum, barley, rice, rye, milo, sunflower, flax, soybeans, and peanuts. The production of these crops represents between 35 to 40 percent of the gross national product of the agriculture produce and between 35 to 40 percent of the exports (Fernandez and Acuna 1979).

Although Argentina is known for its beef and wheat production, corn ranks first in total grain production with an average of 8.5 million bushels per year (1972/73 to 1977/78 seasons).

About half of the corn is used internally and the other half is exported. Argentina ranks second in corn exports with about 9 percent of the total traded worldwide (Table 1). The corn produced in Argentina is of the "flint" type, which is richer in carotene and provitamin A than the "dent" type. Italy and Spain, with 44 and 15 percent, respectively, are the main importers of this type of corn. Their preference is based on the quality factors previous mentioned plus the high proportion of nutrient starch of the "flint" type corn.

3.1 Drying and Storage in Argentina

More than 70 percent of the corn produced in Argentina is artificially dried (de Dios and Puig, 1981). As in the United States the cross-flow dryer design is the most commonly used, although some grain terminals use a combination drying technique in order to improve the grain quality.

About 80 percent of the storage facilities in Argentina are located within the production zones; only 20 percent of the corn is held at the export ports (Fernandez and Acuna, 1979). Although most of the grain is handled in bulk, 40 percent is still stored and handled in 132 lb bags. This practice requires excessive labor and capital. The yute bags can not be used more than twice; the associated costs of higher handling costs and lower storage capacities are further disadvantages of bag handling/storage.

The Junta Nacional de Granos (a government institution) owns 43 percent of the Argentinian storage facilities, the Agrarian Cooperatives 23 percent, private elevators 18 percent and the processing industry 16 percent. Although the total storage capacity has increased in the last five years from 1975 to 1980, Argentina still has a storage capacity deficit of more than 353.6 million bushels (Fernandez and Acuna, 1979). This problem is partially offset by the fact that there are about 137.5 million bushels of storage capacity at the farm level. If Argentina is to increase its grain production, the problem of storage should be considered the number one priority. It is obvious that no expansion in grain production can be expected without first increasing the storage capacity.

CHAPTER 4

LITERATURE REVIEW

4.1 Cross-flow Drying

Commercial cross-flow dryers are often called, in the trade, screen-column dryers. The conventional models are non grain-mixing type dryers. They are simple in construction and in operation and they are generaly lower in first cost than most other dryer configurations. However, the operating cost of cross-flow dryers is detrimentally affected by the periodic replacement of the screens (Hawk et al., 1978).

In the cross-flow drying method, wet grain from the wet holding bin at the top flows down the columns, where it is dried to the appropriate moisture content, cooled and unloaded at the bottom (Figure 4.1). Drying and cooling are accomplished by transverse air flow, the air acting as

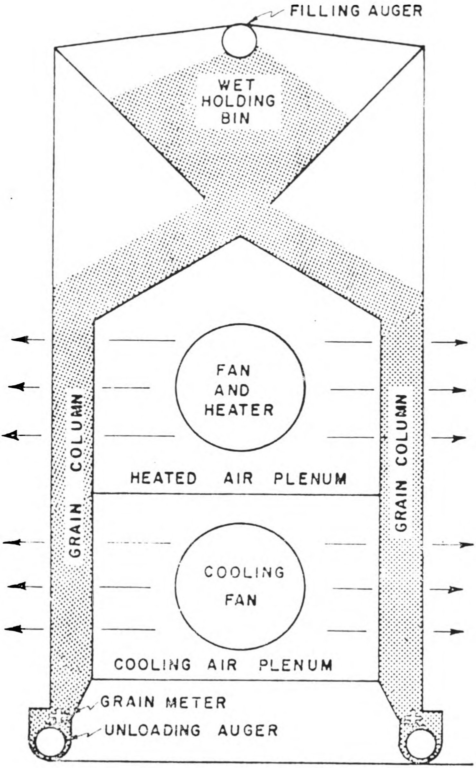


Figure 4.1. Schematic of a conventional continuous flow cross-flow grain dryer (Brooker et al.,1974).

a vehicle for carrying heat to or from the grain and removing the evaporated moisture. The grain flow rate is regulated by a metering device at the lower end of the column; it responds to a temperature sensor located in the grain column near the lower edge of the drying section.

One of the basic disadvantages of a cross-flow dryer is the development of a moisture gradient across the column as the grain flows down (Paulsen and Thompson, 1973). Grain nearest the inside of the column tends to overheat and over-dry in the drying section and to over-cool in the cooling section of the dryer while grain in the outer portion is under-dried and under-cooled (Gygax et al., 1974). Gustafson and Morey (1980) quantified the moisture gradient across the drying column of some basic cross-flow dryers. Differences across the column as large as 20 percent for moisture, 120 F for temperature and 50 percent for breakage susceptibility were observed. The drying efficiency of the basic cross-flow dryers is less than desirable and is normally over 3000 BTU/lb (6978 kj/kg) of water removed (Bakker-Arkema et al., 1979).

In cross-flow systems the grain is mixed following the cooling stage in an effort to reduce the temperature and moisture gradient across the column. Thorough mixing has been shown to result in the dried grain to approach to within one percent of its equilibrium moisture content (White and Ross, 1971).

Reversing the air flow during a second drying stage minimizes overdrying by applying the heated air to the wettest grain. Converse (1972) discussed the first commercial cross-flow dryer with reverse airflow and air recycling. This design (shown in Figure 4.2) became the model for a number of similar commercial dryers in the United States and has been modeled by Lerew et al. (1972). It was determined by Morey and Cloud (1973), and Paulsen and Thompson (1973) that the difference in moisture content was reduced by roughly 60 percent, at the cost of lowering the grain flow rate by 2 to 8 percent and the overall dryer efficiency due to lower average grain temperatures. A different cooling method has also aided in reducing the gradient in the grain column. The conventional cooling configuration forces ambient air across the grain and exhausts it, which causes the greatest thermal shock on the grain by bringing the coolest air in contact with the hottest grain. By drawing ambient air through the coolest grain, thermal shock is reduced and the air is warmed. This method not only yields better quality grain, but also enhances efficiency, as the preheated air is used in the burner (Brooker et al., 1974).

A modified cross-flow dryer (air recycling and reversing) was 50 percent more energy efficient than the comparative basic model (Lerew et al., 1972).

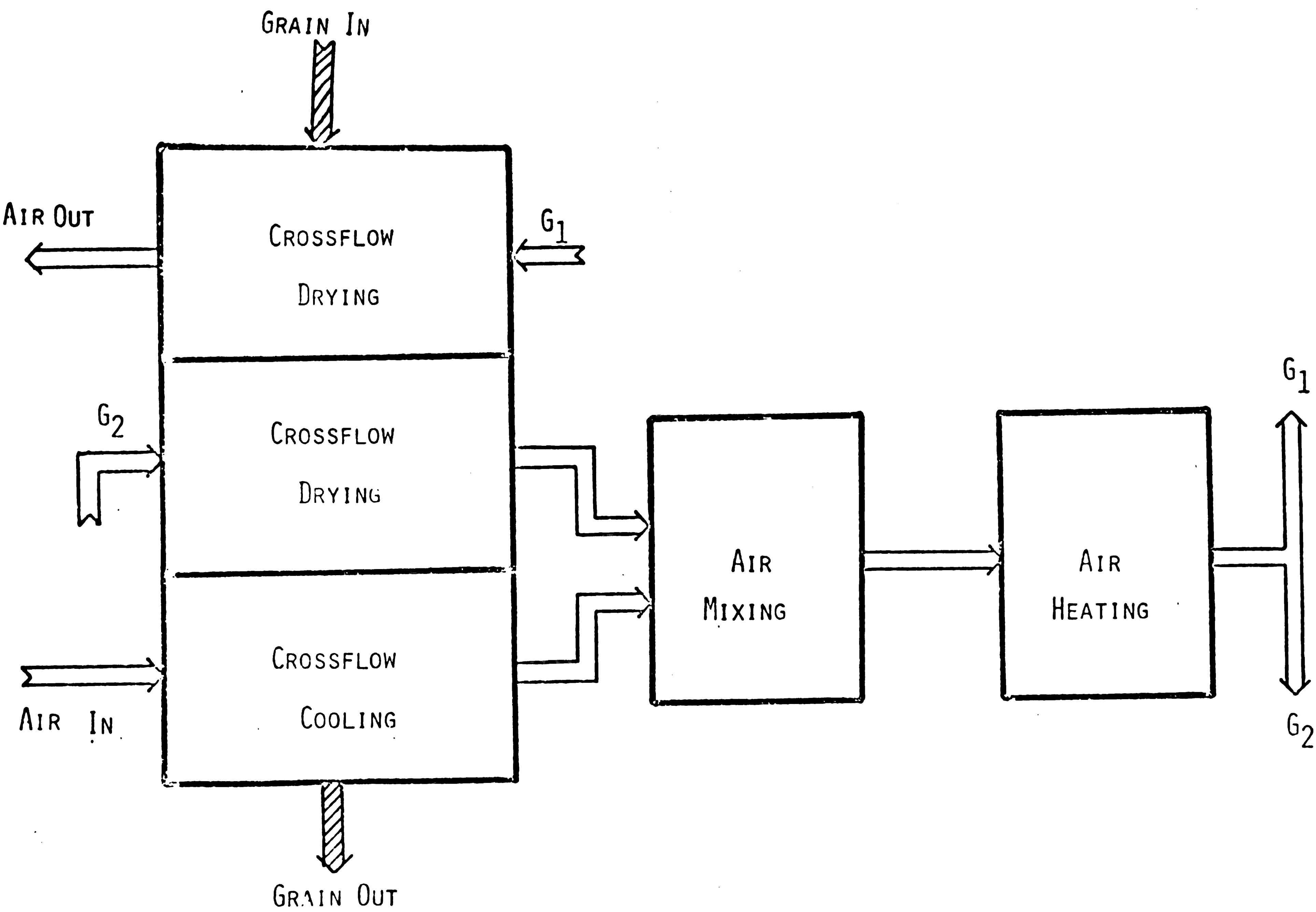


Figure 4.2. Schematic of a cross-flow dryer with air-reversal and air-recirculation (Hart-Carter).

Bakker-Arkema et al. (1972) reported that the modified cross-flow dryer was more energy efficient than an early version of the concurrent-flow dryer. The improvement in energy efficiency was attributed to the recirculation of 50 percent of the total air employed (Bakker-Arkema et al., 1972; Bauer et al., 1977). Bakker-Arkema et al. (1979) found that a modified cross-flow dryer was 42 percent more energy efficient than the basic cross-flow dryer. Pierce and Thompson (1981) found that modification of a conventional cross-flow dryer (air reversal and recycling) decreases the energy consumption by 37 percent and the moisture content differential by 78 percent while maintaining dryer capacity.

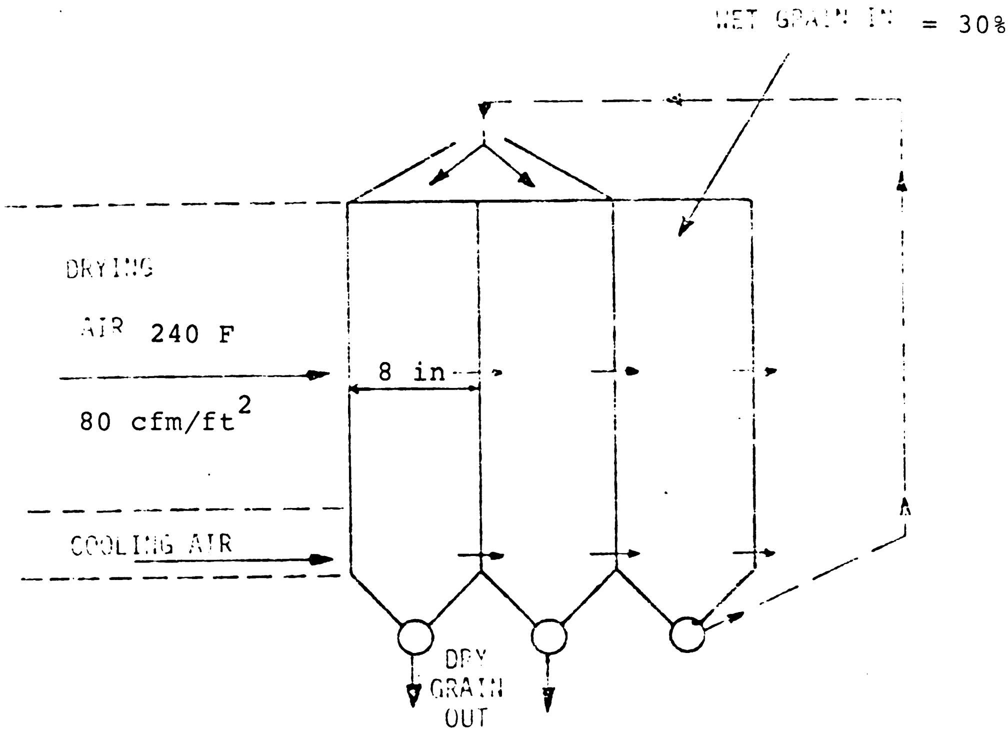
The so called "grain turn-flow device" is an addition to a conventional cross-flow dryer in order to decrease the temperature and moisture gradients across the grain column. This device switches the dryer grain from the air inlet side of the column to the air outlet side and the wetter grain from the air outlet to the air inlet side (Hawk et al., 1978).

The addition of grain-flow turning and airflow recycling and reversal designs have improved the uniformity of the outlet grain moisture content in commercial cross-flow dryers. The new designs can limit the variation of grain moisture content at outlet to less than two-four percent (50 to 80 percent smaller than of the conventional designs, Hawk et al., 1978). Unfortunately, the new designs have complicated dryer construction and in some cases resulted in decreased airflow (and thus capacity) and in increased fire hazzards.

Morey and Cloud (1973) modeled a multiple-column cross-flow dryer. In their design (Figure 4.3), grain from the column furthest from the air inlet is recycled through columns nearest to the air inlet. Multiple column dryers result in a decreased moisture content differential at the grain outlet, an increased energy efficiency, and decreased operating costs (Morey and Cloud, 1973). Bakker- Arkema et al. (1978) pointed out that multiple-columns designs present a complex control problem requiring accurate moisture metering.

4.2 Cascade Drying

Cascade dryers (also called rack, baffle or mixed flow dryers) used to be among the most popular commercial dryers (Westelaken and Bakker-Arkema, 1978). They consist of a housing containing alternate rows of perforated or inverted V-baffles which act as air inlet and outlet ducts. The grain flows downward by gravity over the baffles and is exposed alternately to inlet and outlet air. Considerable lateral mixing of the grain takes place resulting in a more



Moisture content (%)	15.0	15.0	25.9
MC differential (%)	6.2	3.7	4.3
Corn temperature (F)	50	70	136
Capacity (bu/hr-ft^2)	.40	.18	.58

Figure 4.3. A multiple-column cross-flow dryer (Morey and Cloud, 1973).

uniform air exposure and smaller moisture differential of the grain in a cascade dryer than in a conventional cross-flow dryer. Rising manufacturing costs and clean air demands have decimated the number of rack type dryers manufactured (Westelaken and Bakker-Arkema, 1978). Figure 4.4 shows a schematic of a cascade dryer.

4.3 Concurrent-flow Drying

Concurrent-flow dryers have recently become commercially available (Brook, 1977). In 1955 Oholm patented a concurrent-flow grain dryer (Hawk et al., 1978). Since the early 1970's a United States company has manufactured on-farm concurrent-flow grain dryers (Graham, 1970). Anderson (1972) designed the first commercial sized one-stage concurrent-flow dryer. Ten units (each with a capacity of 1000 bushel per hour, five points moisture removal) of the Anderson design have been operational since the mid 1970's in Illinois (Hawk et al., 1978). Westelaken (1977) described the first commercial multi-stage concurrent-flow grain dryer. Hawk et al. (1978) reported that a number of Russian dryer design have incorporated the concurrent-flow principle.

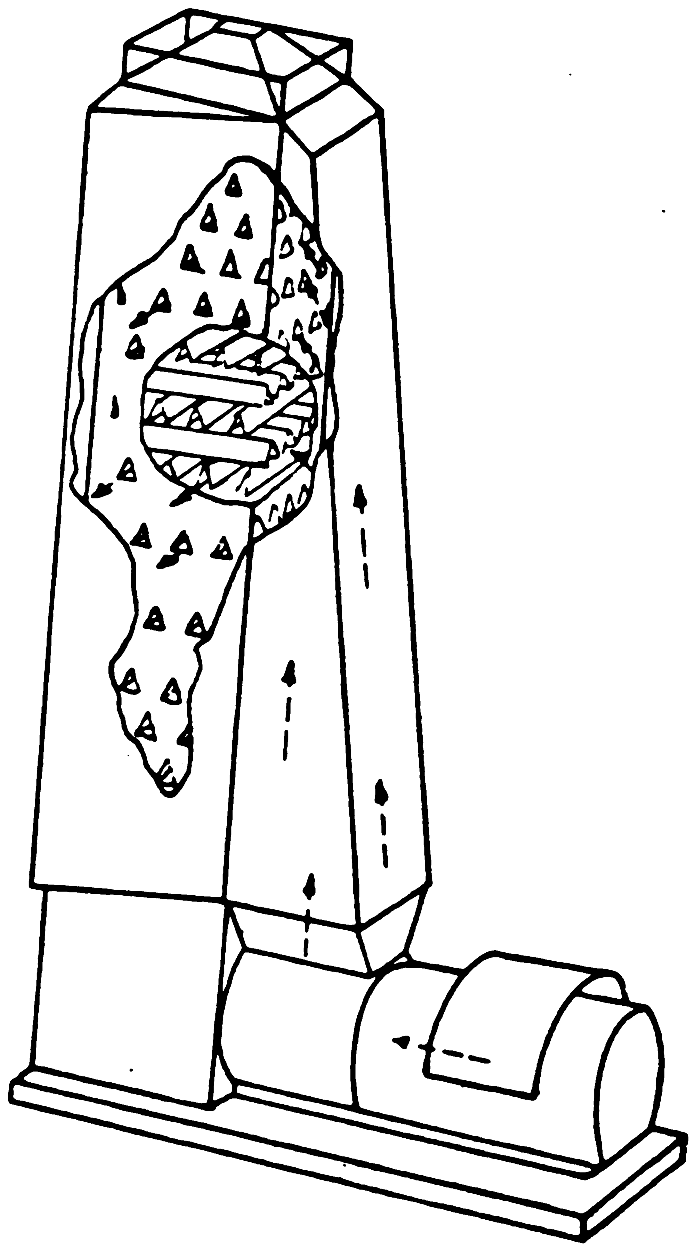


Figure 4.4. Schematic of a cascade grain dryer (Bakker-Arkema et al., 1978).

In a concurrent-flow dryer, the air and the grain flow in the same direction through the dryer. An schematic of such dryer design is shown in Figure 4.5. In this dryer type the hottest air encounters the wettest kernels and therefore the drying air is cooled rapidly due to the high rate of evaporation (Brook, 1977). This permits the use of drying air temperatures much higher than in cross-flow dryers. This in turn results in a higher energy efficiency of concurrent-flow dryers (Bakker-Arkema et al., 1972). The air and product temperatures versus grain depth in a concurrent-flow drying section are illustrated in Figure 4.6. As can be seen (Figure 4.6) the kernel temperature remains considerably below the air temperature in the top layers of the dryer. This is due to the fact that the kernels during this period of high evaporation are not exposed to the hot air inlet for a long period of time (Farmer et al., 1972). As the grain and the air move through the dryer, their temperatures equilibrate (Figure 4.6). The cooling of the drying air, the increase in the relative humidity of the drying air, and the increase in the product equilibrium moisture content lead to a decrease in the driving forces of the drying process.

In a concurrent-flow dryer every kernel is subject to the same treatment; therefore, the moisture and temperature gradients among kernels in a

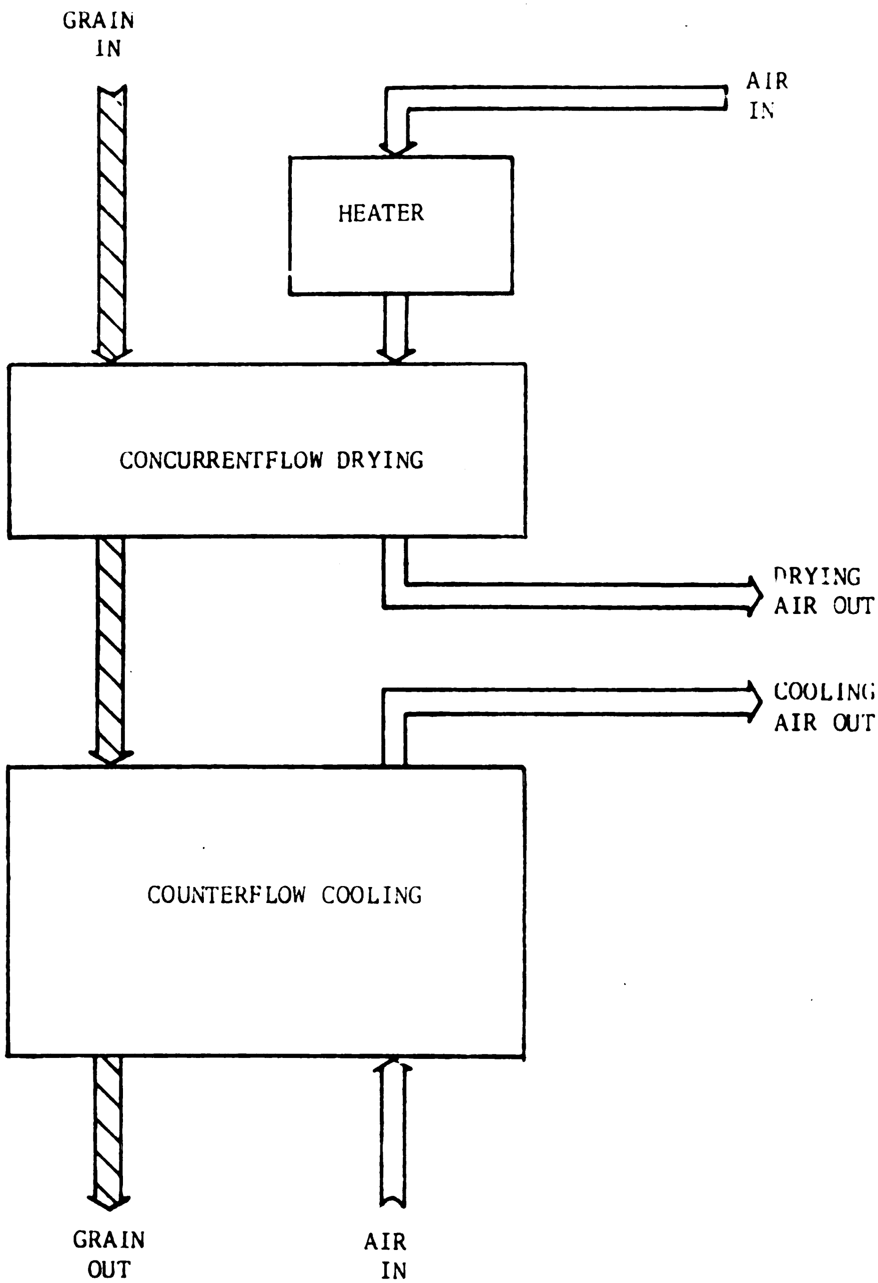


Figure 4.5. Block diagram of a single-stage concurrent-flow dryer with a counterflow cooler (Brooker et al., 1974).

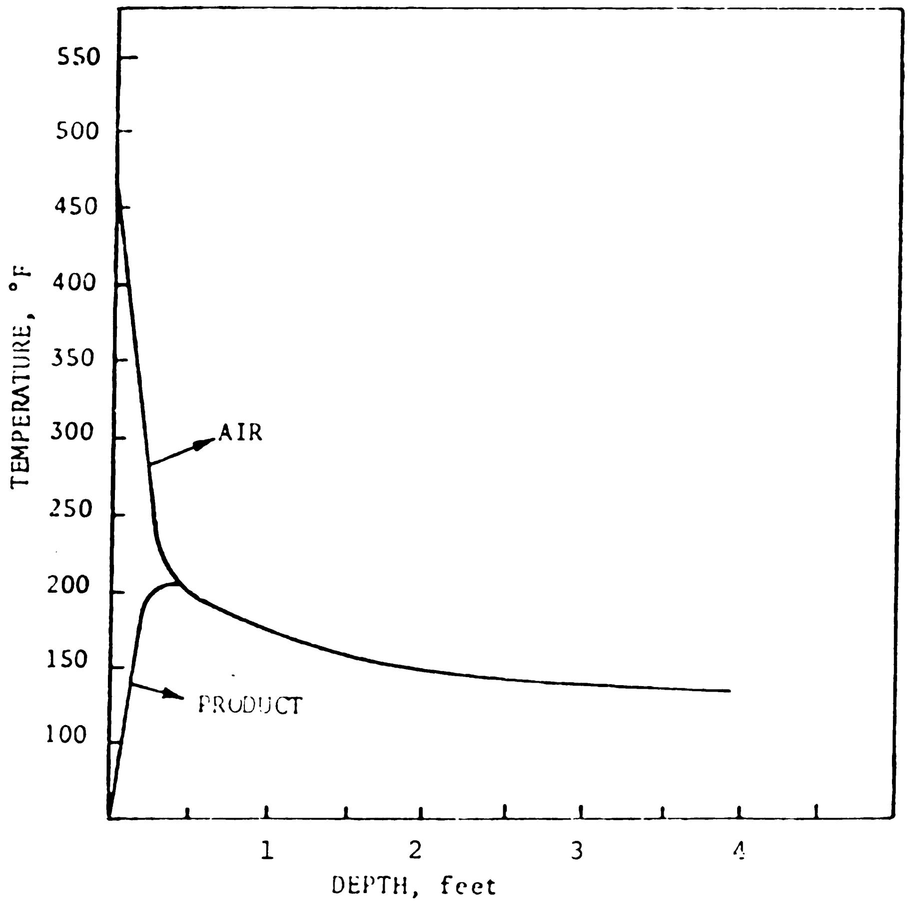


Figure 4.6. Air and product temperatures versus depth for a single-stage concurrent-flow dryer.

cross-flow dryer are non existent in this type of design. Furthermore, the continuous decrease of the grain temperature as the depth of the drying bed increases (Figure 4.6), alleviates the drying stresses and reduces stress cracking and mechanical breakage during subsequent handling (Brook, 1977).

The basic design of a concurrent-flow dryer has one concurrent flow drying section with one counter-flow cooling section (Figure 4.5). This principle of cooling has a high thermal efficiency and has also the advantage that the coldest air encounters first the coldest grain, thereby limiting the thermal stresses of the grain and hence the development of stress cracks (Gygax et al., 1974).

If moisture removal in a single-stage concurrent-flow dryer is over ten points (25.5 to 15.5 percent) the drying capacity is limited. Furthermore, due to the low grain velocities the drying product is subject to high product temperatures and a relatively severe drying treatment (Bakker-Arkema et al., 1977).

Bakker-Arkema et al. (1972) reported that the air moved and exhausted through a cross-flow dryer is eight to ten times larger and the air velocities significantly higher than of a comparable concurrent-flow dryer. Thus, the pollution characteristics of the concurrent-flow type are better than of conventional cross-flow configurations.

A more recent development in concurrent-flow dryers is the multi- stage design (Figure 4.7). This type permits the use of higher grain velocities, and therefore higher inlet air temperatures can be used. It also incorporates, between two drying stages, a tempering or steeping zone. This type of dryer was the first to use this technique (Bakker-Arkema, 1982). Advantages of multi-stage dryers over single- stage models are (Westelaken and Bakker-Arkema, 1978): (1) increased capacity, (2) improved grain quality, (3) greater contralability, and (4) improved thermal efficiency.

Some commercial three-stage concurrent-flow dryers incorporate the recycling of the air from the second and third stages (Hawk et al., 1978). The energy efficiencies in such recirculating dryers are well below 1700 BTU (3954 kj/kg) per pound of water removed (Bakker-Arkema et al., 1978).

Although concurrent-flow grain dryers have successfully dried corn, pea beans, wheat, soybeans, and rice, low-cost energy and less expensive dryer configuratiions have delayed marketing of the concurrent-flow dryer (Dalpasquale, 1981).

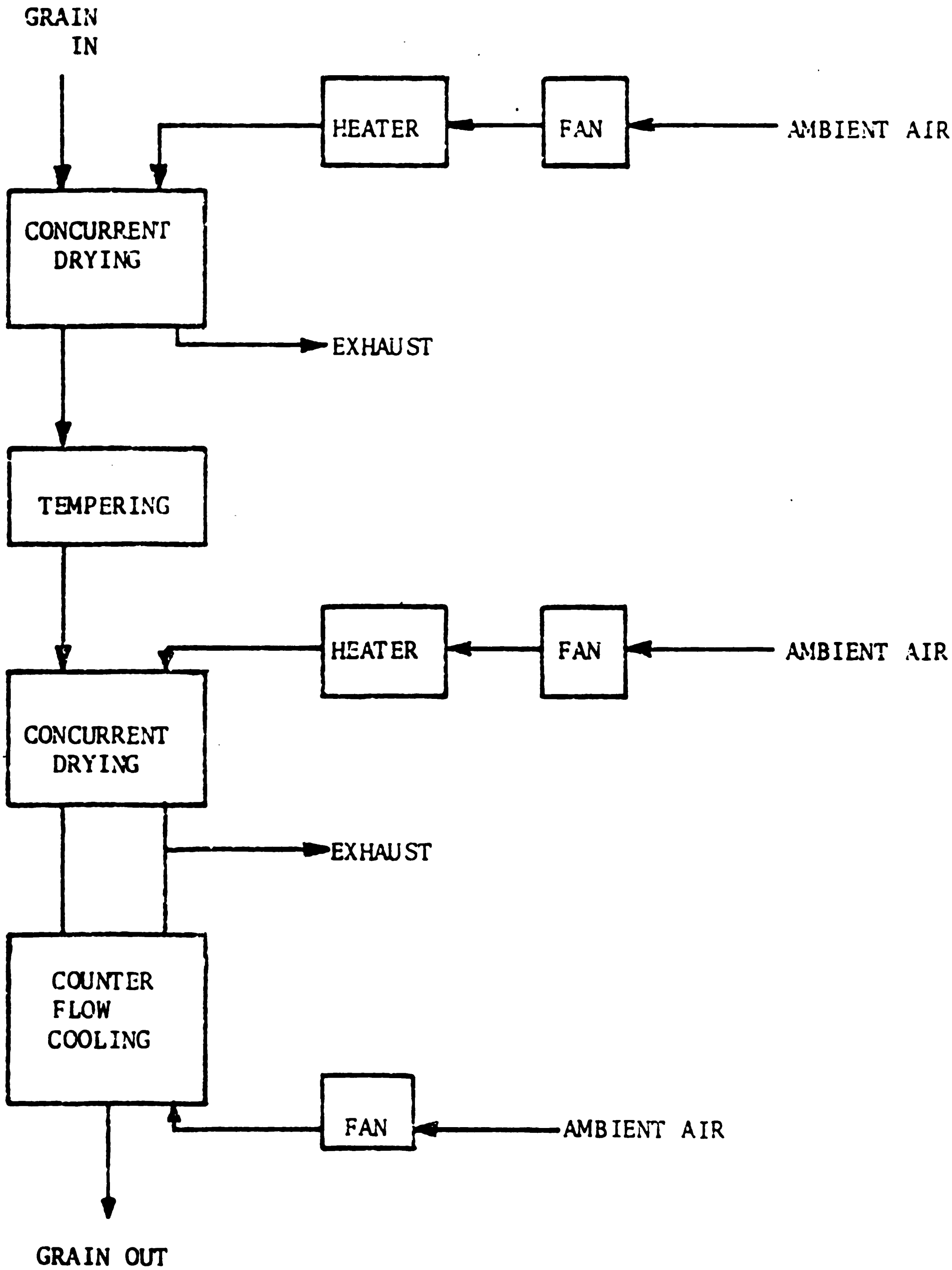


Figure 4.7. Block diagram of a two-stage concurrent-flow dryer with counterflow cooler.

4.4 Tempering

High temperature drying systems lead to moisture gradients and to a lesser extent temperature gradients within individual kernels during drying. Since the surface dries faster than the center of the kernel, the outer portion can act as a barrier to outward moisture diffusion, slowing the drying rate and increasing grain damage due to stress cracking (Brooker et al., 1974).

Internal moisture gradients of kernels are minimized by a treatment called tempering or sweating. During tempering the hot grain is held without air treatment, thereby allowing the moisture and temperatures to equilibrate within the individual kernels prior to further drying or cooling (Sabbah, 1971).

Sabbah et al. (1972) reported that increases in drying/cooling rate were proportional to increases in the length of tempering time within a certain time/temperature range (at 140 F, 23.3 percent moisture content dry basis and 9.9 hours maximum tempering time). Thompson and Foster (1967) found that the maximum amount of moisture was removed from grain at 140 F and 21 percent moisture content (dry basis) when the grain was tempered for eight hours. Emam et al. (1979) found a significant reduction in kernel breakage after tempering at 203 F. Corn which was not tempered displayed a breakage of 25.14 percent at 13.9 percent moisture content, while corn which was tempered for three hours had only 9.4 percent breakage. They found no significant difference in grain quality between tempering times of 1, 2 or 3 hours with grain temperature of 203 F. When the final moisture content increased, the amount of grain breakage decreased. Corn at 18.3 percent moisture content showed only 4.8 percent breakage without tempering. Thus, the final moisture content desired will dictate the necessary steps to ensure maximum quality in the dried grain.

The tempering time should be as short as possible to achieve acceptable moisture equilibration, since prolonged exposure to the hot, humid conditions can deteriorate grain quality through increased respiration, chemical changes, and insect and microbial activity (Steffe and Singh, 1980). Shorter tempering also benefits the logistics of drying.

4.5 Effects of Drying on Grain Quality

There are five factors that determine the official commercial grade of corn in the United States (Hill and Jensen, 1976). As can be seen from Table 4.1, the standard

Table 4.1: Grades and Grade Requirements for Corn.[1]

GRADE	Minimum test weight per bushel	Maximum limits of - -			
		Moisture	Broken corn and foreign material	Damaged kernels	
				Total	Heat damaged kernels
	Pounds	Percent	Percent	Percent	Percent
U.S. No.1	56.0	14.0	2.0	3.0	.1
U.S. No.2	54.0	15.5	3.0	5.0	.2
U.S. No.3	52.0	17.5	4.0	7.0	.5
U.S. No.4	49.0	20.0	5.0	10.0	1.0
U.S. No.5	46.0	23.0	7.0	15.0	3.0

[1] After Hill and Jensen (1976)

grades for corn only consider test weight, moisture content, broken and foreign material and damaged kernels (total and heat damage kernels). Other grain properties such as millability, viability, and susceptibility to breakage which are quality related are presently not considered in the corn standards of the United States (Brooker et al., 1974). Several of the factors included in the official grades do not provide any useful information on the feeding value of the corn (Hill and Jensen, 1976).

4.5.1 Test Weight

Test weight of corn is defined as the weight of grain required to fill a bushel. Test weight is generally used as an indicator of grain quality. This is probably true for wheat because it serves as an index of the flour yield which may be expected (Bakker-Arkema et al., 1978). However,test weight for corn is less important and does not serve as a quality indicator (Bakker-Arkema et al., 1978).

Test weight generally increases during the drying process. Hall and Hill (1973) found that the change in test weight during the drying process is affected by the drying air temperature, initial and final moisture content, grain variety, and mechanical damage. High drying temperatures result in smaller test weight increased (Hill and Jensen, 1973, Gustafson and Morey, 1979). Overdrying and using very high air temperatures lowers the final test weight (Hall and Hill, 1973).

Machine harvested and artificially dried corn have a lower final test weight than field dried corn (Peplinski et al., 1975). The rate of test weight increase due to artificial drying is decreased in proportion to the degree of mechanically damaged corn (Hall and Hill, 1973; Gustafson and Morey 1979).

Higher initial moisture content corn will have higher final test weight if dried at the same temperature and to the same final moisture content (Hall and Hill, 1973).

Combination drying results in a higher final test weight increase when compared to high temperature drying (Bakker- Arkema, 1982).

4.5.2 Stress Cracks and Broken Kernels

Stress cracks are defined as the cracks in the starchy endosperm of the kernel which do not rupture the seed coat (Thompson and Foster, 1963).

Using hot air (140 F to 240 F) to dry grain will increase the percentage of stress cracking (Thompson and Foster, 1963, Bakker-Arkema et al., 1978).

Thompson and Foster (1963) found that the amount of moisture reduction as well as the speed of drying contributes to stress crack formation.

If corn is not immedeately cooled after artificial drying but is tempered and cooled over a period of six hours, the breakage is independant of the drying rate (Katic, 1973).

Rapid cooling of high temperature corn causes a high percentage of stress crack development (White and Ross, 1972). In a test conducted by Thompson and Foster (1963), corn was heated in an oven to 230 F. Due to the fact that no moisture was removed during the heating process, very little stress crack development was reported, even when the kernels were cooled rapidly.

White and Ross (1972) found that slow cooling reduces the percentage of stress cracked kernels. Stress cracking decreases as corn is dried from a lower initial moisture content (Ross and White, 1972).

4.5.3 Predicting Susceptibility to Breakage

The degree of stress cracking of the kernels which occurs during the harvesting and drying processes will influence the susceptibility of corn to breakage during handling (Brook, 1977). Hall (1974), reported that corn dried at an air temperature of 240 F showed two to three times more damage during subsequent handling than corn dried at an air temperature of 70 F. Artificially dried shelled corn, using heated air, is two to three times more susceptible to breakage than corn dried with natural air (Thompson and Foster, 1963; Katic, 1973). Gustafson and Morey (1979) found that increasing the drying air temperature of a high temperature dryer leads to an amplification of the breakage susceptibility increases associated with drying. Mensah et al. (1976) reported that corn dried at lower temperatures has a greater resistance to impact damage than corn dried at higher air temperatures.

Breakage susceptibility changes for corn dried to a final moisture content above 18 to 20 percent are small while for grain dried below 18 to 20 percent the breakage susceptibility increases rapidly (Gustafson et al., 1978; Fortes and Okos, 1979; Gustafson and Morey, 1979; Gustafson and Morey, 1981).

Many attempts have been made to develop a testing device for predicting the susceptibility to breakage of grain. Thompson and Foster (1963) evaluated three breakage testers or testing methods. They found that the Stein breakage tester gave the most consistent measure of breakage susceptibility.

Any breakage tester indicates only breakage susceptibility, the actual breakage will depend on the number and severity of the handling operations the grain is subjected to (Stephens and Foster, 1976). Breakage tests will show the relative breakage susceptibility of different lots of corn. Standardization of the testing procedure should be a must if the breakage tester is to be used in official grading procedures.

Miller et al. (1979) have developed a standard procedure for measuring the breakage susceptibility of corn (Appendix B).

4.6 Energy Efficiency Calculation

Grain dryers are usually rated by total drying capacity only (Bakker-Arkema et al., 1978b). Although some manufacturers advertise that their dryers are more efficient than others, the energy efficiency is very seldom listed.

The energy efficiency of a grain drying process or grain dryer is defined (Bakker-Arkema et al., 1978b) as "the total energy required to remove a unit weight of moisture from the grain under standard conditions", and is usually expressed in BTU per pound of water removed (kj/kg). The energy efficiency of corn grain drying systems varies from 1300 (3020 kj/kg) to 3800 (8840 kj/kg) BTU per pound of water removed (Maddex and Bakker-Arkema, 1978).

The variation in energy efficiency can be attributed to the following factors: 1) rate of airflow, 2) temperature and humidity of the drying air, 3) type of dryer, 4) management of the drying system, 5) conditions of the grain and weather, and 6) quality of design. Low airflows combined with limited additional heat usually yield good efficiencies but a reduced drying capacity. In the case of high-temperature drying, increasing the drying air temperature will result in the most efficient moisture removal (Aguilar and Boyce, 1966; Maddex and Bakker-Arkema, 1978).

Aguilar and Boyce (1966) proposed a ratio termed the Total Heat Efficiency (T.H.E.) and an alternative ratio termed the Effective Heat Efficiency (E.H.E.). The T.H.E. ratio is defined as the ratio of sensible heat used in the drying process to the sum of the sensible heat in the ambient air and the heat added; the E.H.E. ratio is defined as the ratio of the sensible heat used in the drying process to the sensible heat available in the drying air.

Due to the fact that the T.H.E. ratio is a function of the ambient wet bulb temperature (which is not dependent on the dryer), it is not possible to compare driers through their T.H.E. values unless some fixed basis is established.

The E.H.E. ratio in contrast considers the sensible heat in the drying air as being the effective heat available for drying. Consequently, the E.H.E. ratio can be used to compare directly the effect of variable drying parameters.

Bakker-Arkema et al. (1973, 1978) proposed a standardized test procedure and a method for calculating energy requirements using the Dryer Performance Evaluation Index (DPEI). The DPEI is defined as the total energy required by a dryer to remove one pound of moisture from the grain under standard conditions. The total energy includes the energy required to heat the drying air, the energy to drive the drying and cooling fans, and the energy to move the grain. Temperature and relative humidity of the air, and moisture content and temperature of the grain are the conditions that are specified.

Morey et al. (1976) proposed the following criteria to evaluate grain dryers:

A. energy requirements

a. energy to heat the drying air;

b. energy to move the drying air:

i. energy to the fan motor

ii. equivalent amount of fossil fuel energy required to generate electrical energy for the fan;

c. total energy to heat the air and drive the fan;

B. uniformity of final moisture content (the differential between the column inside and outside MC when the grain is dicharged from the dryer).

None of the previously proposed standards or indexes has as yet been accepted by the United States grain drying manufacturing industry. Bakker-Arkema et al. (1978b) and Bakker-Arkema (1982) cooperated with the FIEI (Farm and Industrial Equipment Institute) and proposed that dryers should be tested experimentally under conditions approximating standard conditions. Tables 4.8

and 4.9 - 4.10 show the proposed standard conditions and the data to be determined for a dryer performmance evaluation for corn. The experimental test should be duplicated by simulation in order to determine the hybrid drying factor of the corn and the energy efficiency factor of the dryer.

The hybrid drying factor is a factor build in the XFLO drying program, which would account for different drying characteristics of the different varieties or hybrids of corn.

The energy efficiency factor is calculated by dividing the energy measured experimentally over the simulated by the drying model.

Bakker-Arkema (1982) also proposed that the experimental results should be corrected to a set of standard conditions (Table 4. 11).

Table 4.8: Proposed standard conditions for the performance evaluation of automatic batch and continuous flow grain dryers, drying shelled corn (From Bakker-Arkema, 1980).

Inlet corn moisture content, % w.b.	20.5 ± 1.5 25.5 ± 1.5
Outlet corn moisture content, % w.b. drying dryeration combination drying	 15.5 ± 1.0 18.0 ± 1.0 22.5 ± 1.0
Ambient air temperature, F	60 ± 15
Ambient relative humidity, %	60 ± 30
Atmospheric pressure, inc. Hg	30 ± 0.1
Inlet BCFM, %	≤ 3.0
Inlet corn temperature, F	60 ± 15
Test period, Number of dryer exchanges	3

Table 4.9: Drying parameters and performance characteristics of a continuous-flow grain dryer (From Bakker-Arkema, 1980).

Conditions	Units	Test Type			
Ambient					
Air Temperature	F				
Relative Humidity	%				
Barometric Pressure	in.Hg				
Grain					
Type of Grain					
Variety of Grain					
Moisture Content of Wet Grain	%, w.b.				
Moisture Content of Dried Grain	%, w.b.				
Temperature of Wet Grain	F				
Temperature of Dried Grain	F				
BCFM of Wet Grain	%				
BCFM of Dry Grain	%				
Breakability Index of Wet Grain	%				
Breakability Index of Dried Grain	%				
Test Weight of Wet Grain	lb/bu				
Test Weight of Dried Grain	lb/bu				
1000 - Kernel Weight, Dried Grain	lb				
Dryer					
Dryer Holding Capacity	ton				
Cooler Holding Capacity	ton				
Drying Air Temperature	F				
Cooling Air Temperature	F				
Dryer Static Pressure	in.WC				
Cooler Static Pressure	in.WC				
Fuel Consumption Rate	gal/hr				
Power Consumption Rate	kW				
Output Rate of Dried Grain	ton/hr				
Standard Results		1*	2*	3*	4*
Fuel Consumption Rate	gal or ft^3/ton				
Power Consumption Rate	kWh/ton				
Output Rate of Dried Grain	ton/hr				
Evaporation Rate	lb H_2O//hr				
Specific Energy Consumption	BTU/lb H_2O				
Specific Evaporation Rate	lbs H_2O/gal or ft^3 of fuel				

*1 - Drying from 20.5 - 15.5%
*2 - Drying from 25.5 - 15.5%
*3 - Dryeration from 25.5 - 18:0%
*4 - Combination Drying from 25.5 - 22.5%

Table 4.10: Drying parameters and performance characteristics of a batch type grain dryer (From Bakker-Arkema, 1980).

Conditions	Units	Test Type			
Ambient					
Air Temperature	F				
Relative Humidity	%				
Barometric Pressure	in. Hg				
Grain					
Type of Grain					
Variety of Grain					
Moisture Content of Wet Grain	%, w.b.				
Moisture Content of Dried Grain	%, w.b.				
Temperature of Wet Grain	F				
Temperature of Dried Grain	F				
BCFM of Wet Grain	%				
BCFM of Dry Grain	%				
Breakability Index of Wet Grain	%				
Breakability Index of Dried Grain	%				
Test Weight of Wet Grain	lb/bu				
Test Weight of Dried Grain	lb/bu				
1000 - Kernel Weight, Dried Grain	lb				
Dryer					
Dried Batch Weight	ton				
Drying Air Temperature	F				
Cooling Air Temperature	F				
Drying Static Pressure	in.WC				
Cooling Static Pressure	in.WC				
Drying Time	min				
Cooling Time	min				
Loading Time	min				
Unloading Time	min				
Fuel Consumption	gal or ft^3 / batch				
Power Consumption	kWh / batch				
Output rate of Dried Grain (incl. loading and unloading)	ton/hr				
Standard Results		1*	2*	3*	4*
Fuel Consumption Rate	gal or ft^3 / batch				
Power Consumption Rate	kWh / batch				
Output Rate of Dried Grain	ton / hr				
Evaporation Rate	lb H_2O / hr				
Specific Energy Consumption	BTU / lb H_2O				
Specific Evaporation Rate	lbs H_2O/gal or ft^3 of fuel				

*1 - Drying from 20.5 - 15.5%
*2 - Drying from 25.5 - 15.5%
*3 - Dryeration from 25.5 - 18.0%
*4 - Combination Drying from 25.5 - 22.5%

Table 4.11: Standard conditions to be used for correcting the experimental results of the performance characteristics of a corn grain dryer (From Bakker-Arkema, 1980).

Inlet corn moisture content, % w.b.	20.5 25.5
Outlet corn moisture content, % w.b. drying dryeration combination drying	 15.5 18.0 22.0
Ambient air temperature, F	60
Ambient relative humidity, %	60
Atmospheric pressure, in. Hg	29.9
Inlet BCFM, %	≤ 3
Inlet corn temperature, F	60

CHAPTER 5

DRYING SIMULATION

Computer models which simulate dryer performance have greatly aided both the dryer design and evaluation. The models are based upon mathematical equations which calculate the moisture loss of the grain as a function of: 1) original moisture content, temperature and physiology of the grain; 2) the relative humidity, temperature and flow rate of the air; and 3) the configuration of the particular dryer.

5.1 Drying Simulation

According to Bakker-Arkema et al. (1974) several physical mechanismms have been proposed for predicting moisture transfer in individual grain kernels:

a. liquid movement due to surface forces (capillary flow);

b. liquid movement due to moisture concentration differences (liquid diffusion);

c. liquid movement due to diffusion of moisture on the pore surfaces (surface diffusion);

d. vapor movement due to moisture concentration differences (vapor diffusion);

e. vapor movement due to temperature differences (thermal diffusion);

f. water and vapor movement due to total pressure differences (hydrodynamic flow).

Dryer simulation equations are based on the basic laws of heat and mass transfer (Bakker-Arkema et al., 1978). The following assumptions are usually made in the development of grain dryer models:

a. the temperature gradients within the individual particles are negligible,

b. the particle to particle conduction is negligible,

c. the airflow and grain flow are plug-type (uniform),

d. $\partial T/\partial t$ and $\partial H/\partial t$ are negligible compared to $\partial T/\partial x$ and $\partial H/\partial x$,

e. the bin or dryer walls are adiabatic with negligible heat capacity,

f. the heat capacities of the drying air and the grain are constant during short time periods, and

g. thin-layer drying and equilibrium isotherm equations are known for the grain to be dried.

Bakker-Arkema et al. (1974) presented the four basic models for drying of beds of grain kernels:

A. Fixed - Bed Model

$$\frac{\partial T}{\partial x} = \frac{-ha}{G_a c_a + G_a c_v H}(T - \theta) \tag{5.1}$$

$$\frac{\partial \theta}{\partial t} = \frac{ha}{\rho_p c_p + \rho_p c_w M}(T - \theta) + \frac{h_{fg} + c_v(T - \theta)}{\rho_p c_p + \rho_p c_w M} G_a \frac{\partial H}{\partial x} \tag{5.2}$$

$$\frac{\partial H}{\partial x} = -\frac{\rho_p}{G_a}\frac{\partial M}{\partial t} \tag{5.3}$$

$$\frac{\partial M}{\partial t} = \text{an appropriate thin layer equation.} \tag{5.4}$$

B. Cross-flow Model

a. four equation model

$$\frac{\partial T}{\partial x} = \frac{-ha}{G_a c_a + G_a c_v H} (T - \theta) \tag{5.5}$$

$$\frac{\partial \theta}{\partial y} = \frac{ha}{G_p c_p + G_p c_a M} (T - \theta) + \frac{h_{fg} + c_v(T - \theta)}{G_p c_p + G_p c_w M} G_a \frac{\partial H}{\partial x} \tag{5.6}$$

$$\frac{\partial H}{\partial x} = -\frac{G_p}{G_a} \frac{\partial M}{\partial y} \tag{5.7}$$

$$\frac{\partial M}{\partial t} = \text{an appropriate thin layer equation.} \tag{5.8}$$

b. three equation model

$$\rho(C_p + MC_w) \frac{\partial T}{\partial t} + G(C_a + HC_v) \frac{\partial T}{\partial x} +$$

$$G[(C_w - C_v)(212 - T) + h_{fg}] \frac{\partial H}{\partial x} = 0 \tag{5.5'}$$

$$\rho\frac{\partial M}{\partial t} + G \frac{\partial H}{\partial x} = 0 \tag{5.7'}$$

$$\rho\frac{\partial M}{\partial t} = f(T,H,M,t) \tag{5.8'}$$

C. Concurrent-Flow Model

$$\frac{dT}{dx} = \frac{-ha}{G_a c_a + G_a c_v H}(T - \theta) \tag{5.9}$$

$$\frac{d\theta}{dx} = \frac{ha}{G_p c_p + G_p c_w M}(T - \theta) - \frac{h_{fg} + c_v(T - \theta)}{G_p c_p + G_p c_w M} G_a \frac{dH}{dx} \tag{5.10}$$

$$\frac{dH}{dx} = -\frac{G_p}{G_a}\frac{dM}{dx} \tag{5.11}$$

$$\frac{dM}{dx} = \text{an appropriate thin layer equation.} \tag{5.12}$$

D. Counterflow Model

$$\frac{dT}{dx} = \frac{ha}{G_a c_a + G_a c_v H}(T - \theta) \tag{5.13}$$

$$\frac{d\theta}{dx} = \frac{ha}{G_p c_p + G_p c_w M}(T - \theta) + \frac{h_{fg} + c_v(T - \theta)}{G_p c_p + G_p c_w M} G_a \frac{dH}{dx} \tag{5.14}$$

$$\frac{dH}{dx} = \frac{G_p}{G_a}\frac{dM}{dx} \tag{5.15}$$

$$\frac{dM}{dx} = \text{an appropriate thin layer equation.} \tag{5.16}$$

Each of the above deep bed models requires a thin-layer or single- kernel diffusion equation for the grain of which the drying is going to be simulated. Because an analytical solution of the system of differential equations is not possible, numerical techniques have been used (Bakker-Arkema et al., 1974).

5.2 Thin-Layer and Diffusion Equations

In drying simulation, the drying zone or bed is assumed to consist of a series of thin layers. In order to be able to simulate a whole drying process, it is essential to have an accurate equation which describes the moisture loss of each layer. These equations are obtained from thin-layer experiments in which a small quantity of the product is dried.

5.2.1 Empirical Drying Equations

Several empirical drying equations have been developed for shelled corn (Bakker-Arkema et al., 1974). The equation proposed by Thompson et al. (1968) for calculating the drying rate of shelled corn at temperatures ranging from 140 F to 300 F , and the equation developed by

Troeger and Hukill (1970) for corn in temperatures ranging from 90 F to 160 F, are used in the Michigan State University drying models used in this study.

A. Thompson et al. (1968) for shelled corn,

$$140 \leq \theta \leq 300 \text{ F:}$$

$$t = A \ln MR + B (\ln MR)^2 \tag{5.17}$$

where:

$$MR = \frac{Mt - Me}{Mo - Me}$$

$$A = -18.6178 + 0.0048843\theta$$

$$B = 427.3640 \exp(-0.03301\theta)$$

B. Troeger and Hukill (1970) for shelled corn,

$$90 \leq \theta \leq 160 \text{ F:}$$

$$t/60 = P_1 (M - M_e)^{q_1} - P_1 (M_o - M_e)^{q_1} \quad \text{for } M_o \geq M \geq M_{x1} \tag{5.18}$$

$$t/60 = P_2 (M - M_e)^{q_2} - P_2 (M_{x1} - M_e)^{q_2} + t_{x1} \quad \text{for } M_{x1} \geq M \geq M_{x2} \tag{5.19}$$

$$t/60 = P_3 (M - M_e)^{q_3} - P_3 (M_{x2} - M_e)^{q_3} + t_{x2} \quad \text{for } M_{x2} \geq M \geq M_e \tag{5.20}$$

where:

$$M_{x1} = 0.40\ (M_o - M_e) + M_e$$

$$M_{x2} = 0.12\ (M_o - M_e) + M_e$$

$$t_{x1} = \left[P_1\ (M_{x1}-M_e)^{q_1} - P_1\ (M_o-M_e)^{q_1} \right] /60$$

$$t_{x2} = \left[P_2\ (M_{x2}-M_e)^{q_2} - P_2\ (M_{x1}-M_e)^{q_2} \right] /60 + t_{x1}$$

$$P_1 = \exp\ (-2.45 - 6.42\ M_o\ 1.25 - 3.15\ rh + 9.62 M_o \sqrt{rh} + 0.030\theta - 0.12\ Va)$$

$$P_2 = \exp \left[2.82 + 7.49\ (rh + 0.01)^{0.67} - 0.0179\,\theta \right]$$

$$P_3 = \left[0.12\ (M_o - M_e) \right]^{(q_1 - q_3)}\ (P_2 q_2/q_3)$$

$$q_1 = -3.98 + 2.87\ M_o - \left[0.019/(rh\quad 0.015) \right] + 0.016\,\theta$$

$$q_2 = -\exp\ (0.810 - 3.11\ rh)$$

$$q_3 = -1.0$$

5.2.2 Diffusion Drying Equation and Diffusion Coefficients

A diffusion type single kernel drying equation gives a more realistic representation of the drying process than the empirical equations. In addition to describing the drying process, a diffusion type equation allows a study in the tempering zone of a dryer of the moisture gradient inside the kernels.

The following spherical diffusion equation is used to represent the change of moisture content over time during the drying process (Crank, 1976):

$$\frac{\partial M}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left[D(M, \theta) r^2 \frac{\partial M}{\partial r} \right] \tag{5.21}$$

Note that the diffusion equation is a function of the moisture content and the temperature in the kernels.

Equation (5.21) is a second order partial differential equation. It can be transformed in a set of coupled ordinary differential equations by the method of lines for numerical solution on a digital computer (Brook, 1977).

Chu and Hustrulid (1968) developed an equation for the diffusion coefficient as a function of moisture content and temperature for corn assuming that the kernel can be represented by a sphere of equivalent radius:

$$D = 1.629 \times 10^{-3} \exp \left[(0.045\theta + 6.806)\ M \frac{2513.00}{\theta + 273.13} \right] \qquad (5.22)$$

Sabbah (1971) predicted the diffusivity of the corn kernel as a function of temperature and moisture content using the following equations:

$$D = (0.00057\ Ma) \quad \exp \left[\frac{-4812}{T + 460} \right] \qquad (5.23)$$

Equations (5.22) and (5.23) are in English units (ft2/hr).

In both equation (5.22) and (5.23) the corn kernel is assumed to be a spherical body with a radius of 0.0161 ft.

5.3 Comparison of Empirical and Diffusion Equations

Table 5.1 shows a comparison of the drying rate of a single corn kernel as calculated by: 1)the Thompson et al. (1968) equation for temperatures between 160 F to 200 F, 2)the Troeger/Hukill (T-H) (1970) equation for temperatures of 50 F to 140 F inclusive, and 3) the Crank (1976) diffusion equation using the diffusion coefficient of Chu and Hustrulid (C-H) (1968) and 4) the one developed by Sabbah (1971).

It can be seen from the data in Table 5.1 that use of the Sabbah (PDE-SAB) diffusion coefficient results in close agreement with the T-H empirical equation in the 50 F to 140 F range. From 160 F and above use of the Sabbah coefficient results in underdrying compared to the T-H equation. The C-H diffusion coefficient always leads to overdrying except at 200 F where the final moisture content is higher than the values calculated with the Thompson et al. (1968) equation.

The MSU cross-flow model can be run using thin-layer or diffusion equations. In the case of the thin-layer equation, the model uses the Troeger and Hukill (1970) empirical thin-layer equation in the 50 to 159 F temperature range; and Thompson et al. (1968) empirical thin-layer equation for temperatures of 160 F and above. For the diffusion option, the model utilize the Crank (1976) diffusion equation with two options: 1) with the Sabbah (1971) diffusion coefficient; or 2) with the Sabbah (1971) diffusion coefficient in the 50 to 160 F temperature range, and the Chu and Hustrulid (1968) diffusion coefficient for grain temperatures of 161 F and above.

The model also incorporates a hybrid drying factor. Tables 5.2 and 5.3 show the drying rate as influenced by the value of the hybrid factor for diffusion and thin-layer equations, respectively.

The humidity ratio used for the calculations of the drying rate of Tables 5.1, 5.2 and 5.3 was 0.006 pounds of moisture per pound of dry air.

Table 5.1: Comparison of the final moisture content of corn (%, w.b.) during drying using empirical and diffusion equations.

50 F (RH 78%)			100 F (RH 15%)			120 F (RH 8%)			140 F (RH 5%)			160 F (RH 3%)			180 F (RH 2%)			200 F (RH 1%)			
(1) PDE SAB	(2) PDE HUS	(3) Tand H	(1) PDE SAB	(2) PDE HUS	(3) Tand H	(1) PDE SAB	(2) PDE HUS	(3) Tand H	(1) PDE SAB	(2) PDE HUS	(3) Tand H	(1) PDE SAB	(2) PDE HUS	(4) Thomp	(1) PDE SAB	(2) PDE HUS	(4) Thomp	(1) PDE SAB	(2) PDE HUS	(4) Thomp	TIME (HR)
25.0	25.0	25.0	24.8	24.6	24.9	24.8	24.3	24.8	24.7	23.9	24.8	24.6	23.4	24.5	24.5	22.5	24.5	24.3	21.3	24.4	0.03
24.5	24.3	24.7	23.1	21.7	23.2	22.3	20.3	22.8	21.6	19.0	22.7	20.8	17.7	20.4	20.0	16.5	19.4	19.2	15.3	18.3	0.45
24.3	24.0	24.5	22.3	20.7	22.4	21.4	19.2	21.8	20.4	17.7	21.6	19.4	16.4	18.9	18.5	15.1	17.5	17.5	13.8	15.9	0.69
24.1	23.7	24.3	21.5	19.7	21.5	20.2	18.0	20.7	19.1	16.5	20.4	18.0	15.0	17.3	16.9	13.7	15.4	15.8	12.4	13.5	1.02
23.8	23.3	24.0	20.5	18.7	20.5	19.1	16.9	19.4	17.8	15.2	19.0	16.6	13.7	15.7	15.4	12.4	13.4	14.2	11.1	11.1	1.44
23.6	23.1	23.9	20.1	18.3	20.0	18.6	16.4	18.9	17.3	14.8	18.3	15.9	13.2	15.0	14.7	11.9	12.6	13.5	10.6	10.2	1.65
23.4	22.9	23.7	19.5	17.7	19.3	17.9	15.7	18.0	16.4	14.0	17.4	15.0	12.5	13.9	13.8	11.1	11.4	12.5	9.8	8.8	2.01

(1) PDE - SAB: Crank (1976) diffusion equation with the Sabbah (1971) diffusion coefficient.

(2) PDE - HUS: Crank (1976) diffusion equation with the Chu and Hustrulid (1968) diffusion coefficient.

(3) Tand H : Troeger and Hukill (1970) empirical thin-layer equation.

(4) Thomp : Thompson et al. (1968) empirical thin-layer equation.

Table 5.2: Drying rate as influenced by the hybrid drying factor using the spherical diffusion equation at 120 F, 8% RH and 25% initial moisture content (D according to Sabbah, 1971)

Time (HR)	Moisture Content (% w.b.)					
	Hybrid Factor					
	0.90	0.95	1.00	1.10	1.20	1.30
0.03	24.79	24.78	24.77	24.75	24.72	24.70
0.18	23.87	23.81	23.75	23.64	23.53	23.43
0.36	22.95	22.86	22.77	22.59	22.41	22.25
0.54	22.18	22.06	21.95	21.72	21.50	21.30
0.72	21.51	21.38	21.24	20.98	20.73	20.50
0.90	20.93	20.77	20.62	20.33	20.06	19.91
1.02	20.57	20.40	20.25	19.94	19.66	19.39

Table 5.3: Drying rate as influenced by the hybrid drying factor using a thin layer equation at 120 F, 8% RH, and 25% initial moisture content (w.b.)

Time (HR)	Moisture Content (% w.b.)			
	Hybrid Factor			
	0.991	0.995	0.998	1.000
0.03	24.67	24.74	24.78	24.84
0.18	23.11	23.53	23.85	24.06
0.36	21.45	22.22	22.81	23.21
0.54	19.96	21.04	21.88	22.44
0.72	18.62	19.97	21.02	21.73
0.90	17.41	18.99	20.23	21.08
1.02	16.67	18.39	19.75	20.78

CHAPTER 6

EXPERIMENTAL

The data utilized in this thesis was gathered from five different sources: 1) cross-flow batch drying data was obtained directly from Silva (1980); 2) an on-farm continuous flow cross-flow dryer with cooling air recirculation was tested at Bellaire, MI; 3) an on-farm continuous flow cross-flow dryer with heating and cooling air recirculation and with tempering and with differential column grain velocity-flow was tested at Salem, KY and at Lucan, Ontario, Canada; 4) a commercial continuous cross-flow dryer with heating and cooling air recirculation and air reversal was tested at Carrollton, MI; and 5) a commercial three stage continuous concurrent-flow dryer was tested at Carrollton, MI.

6.1 Farm Fans AB-8B

Drying data from the results obtained by Silva (1980) on a AB-8B Farm Fans automatic cross-flow-batch dryer (manufacturer Farm Fans, Inc., IN) were employed to make the comparison with the other on-farm dryers. A computer drying model was used to check these results (Appendix A).

The Farm Fans portable dryer model AB-8B is an automatic cross-flow batch dryer. Two grain columns of approximately 12 inch wide and 8 feet long dry batches of approximately 120 bu of wet corn (Figure 6.1). The drying temperatures are controlled by a dual level thermostat. The dryer is provided with an automatic control system which includes:

a. individual magnetic motor starter protection;

b. individual circuit breakers;

c. a cycle counter;

d. a shutdown timer which activates automatically when wet grain tank is empty;

e. twin-stat control on two-stage burner, keeping the

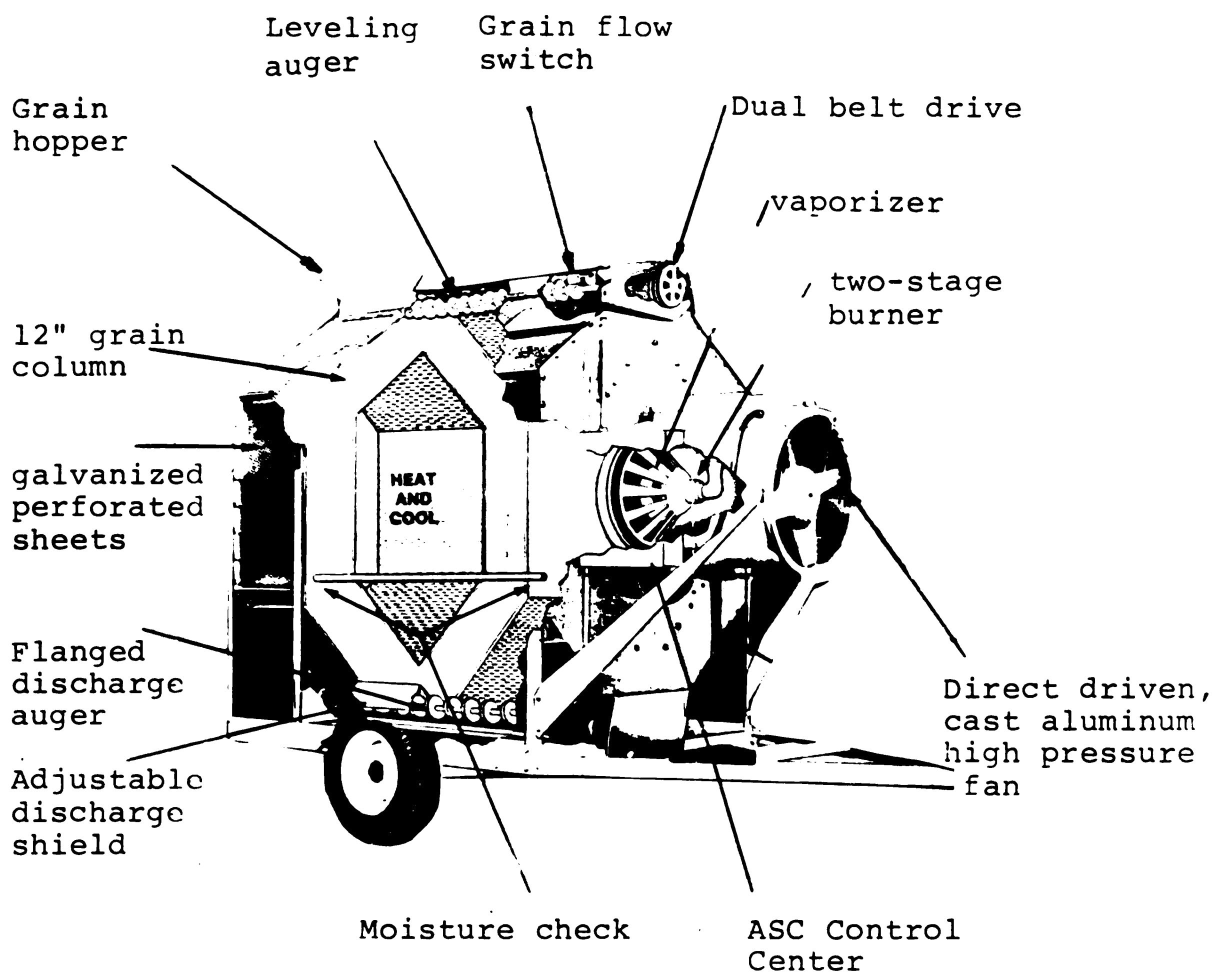


Figure 6.1. Schematic cut-away of the Farm Fans AB-8B.

dryer operating at the desired temperatures regardles of outside weather;

f. an automatic manual switch;

g. a positive cooling control;

h. an hour meter; and

i. a circuit control switch.

The Farm Fans AB-8B specifications are presented in Table 6.1.

6.2 Redex RX-10

Seven tests were conducted with a RX-10 Redex portable continuous cross-flow dryer (manufacturer Modern Farm Systems, Blount, Inc., Webster City, IA) at the Kalchik Farms, Bellaire, MI, during the fall of 1980.

Using corn at different initial moisture contents, the dryer output was varied to give approximately the same final moisture contents. The performance characteristics of the dryer were measured separately for each run. A computer drying model (Schisler, 1982) was later used to check these results (Appendix A).

Table 6.1:Dryer specifications of Farm Fans dryer model AB-8B.

Grain column length, ft		8.0
Total holding capacity, bu		120.0
Less transport:	Length, ft	13.3
	Width, ft	6.0
	Height, ft	8.8
With transport:	Length, ft	16.2
	Width, ft	7.8
	Height, ft	10.0
Fan horsepower, H.P.		13.0
Fan diameter, in.		28.0
Airflow at 3 in. static pressure, cfm		125.0
Heater capacity, BTU/hr		3,000,000.0
Top auger, HP		1.0
Top auger capacity, bu/hr		1,500.0
Bottom auger, HP		1.0
Bottom auger capacity, bu/hr		900.0
Max. running amps., 1 ph., 230 V (with 5 HP load and unload conveyor)		90.0
Max. running amps, 3 ph., 220 V (with 6 HP load and unload conveyor)		60.0
Rated Drying Capacity, wet bu shelled corn per hour		
Dry and cool, 25% to 15%		110.0
Dry and cool, 20% to 15%		155.0
Full heat, 25% to 15%		150.0
Full heat, 20% to 15%		210.0
*Exclusing load and unload time		

Source: Farm Fans Catalog (Bulletin AB-03-3, 1979).

The Redex portable dryer model RX-10 is a continuous cross-flow dryer with reverse-flow cooling. The grain flows from the wet grain garner bin through an approximately 11-inch drying and cooling column to the discharge auger at the bottom of the cooling section (Figure 6.2). The RX-10 specifications are presented in Table 6.2.

Ambient air is drawn through the grain in the cooling section and is thus preheated before it reaches the drying fan and subsequently the LP-heater. The outlet corn moisture content is controlled by adjusting the rpm of the feed rolls and thereby the grain flow rate. The slower the feed rolls turn, the longer the grain will remain in the dryer, and viceversa.

The following are the principal characteristic features of the RX-10:

a. part of the sensible heat of the grain is reclaimed in the cooling section;

b. the ambient air for cooling enters the column where the grain is coldest; [Since the air is warmed as it passes through the grain column, the hottest and driest grain is cooled at a slower rate than if the coolest air entered through the plenum side of the dryer (as is the case in the conventional non

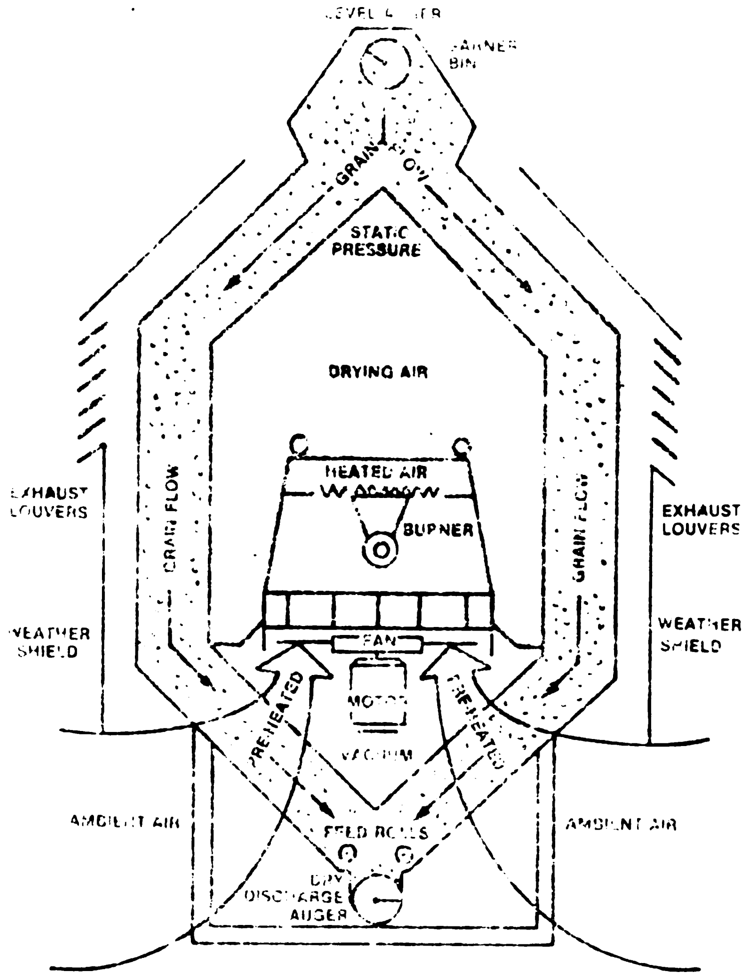


Figure 6.2. Schematic of the Redex RX-10.

Table 6.2: Dryer specifications of Redex dryer model RX-10.

Grain column length, ft	10.0
Total holding capacity, bu	210.0
in drying zone, bu	140.0
in cooling zone, bu	70.0
Length, ft	14.5
Width, ft	7.9
Height, ft	13.0
Fan horsepower, H.P.	15.0
Fan diameter, in.	38.0
Airflow at 3 in. static pressure,cfm /bu	100.0
Heater capacity, BTU/hr	1,700,000.0
Rated Drying Capacity, wet bu shelled corn	
20% to 15%, bu/hr.	240.0
25% to 15%, bu/hr.	150.0

Source: Redex Dryers, operation and Maintenance Manual. Series 9,1980 reverse-flow dryers)]. Therefore, the Redex design can be expected to minimize the checking of the grain during the cooling process.

c. the moisture content gradient across the grain column after the grain has passed the drying section is reduced since the airflows in the drying and cooling sections are in opposite directions;

d. the fan has to overcome the resistance of two columns of grain which results in lower airflow rates at constant horsepower; and

e. chaff and fines that filter through the cooling section pass through the fan-heater and accumulate in the heated air plenum, necessitating periodic cleaning of the dryer.

6.3 Hart-Carter HC-66

Two tests were conducted on a Hart-Carter cross-flow dryer model HC-66 (manufacturer CEA-CARTER-DAY, Minneapolis, MN). The tests were conducted during the 1979 and 1980 fall drying seasons at the Michigan Elevator Exchange terminal, Carrollton, MI. Commercial yellow corn (varieties unknown) available at the terminal was used in the tests. The performance characteristics of the dryer were measured for each run. A computer drying model (Schisler, 1982) was used to analyse the results (Appendix A).

The HC-66 Hart-Carter dryer is a two stage cross-flow dryer with reverse airflow and air recycling (Figure 6.3). The HC-66 specifications are tabulated in Table 6.3. The air in the first stage (Figure 6.3) flows perpendicular to the incoming grain. In the second stage, the drying air direction is reversed. The cooling air flows in the same direction as the air in the second stage. All the air coming from the second stage plus the air from the cooling stage (along with some make-up air) is mixed and used as the inlet air to the burner. This type of arrangement lowers the breakage susceptibility and improves the energy efficiency when compared with conventional cross-flow dryers (Lerew et al., 1972, Gygax et al., 1974, and Bakker-Arkema et al., 1979).

6.4 Blount 10-60

Five tests were conducted on a Blount 10-60 continuous flow cross-flow recirculating dryer (manufacturer Blount, Inc., Commercial Dryer Division, Grand Island, NB). The first three tests were

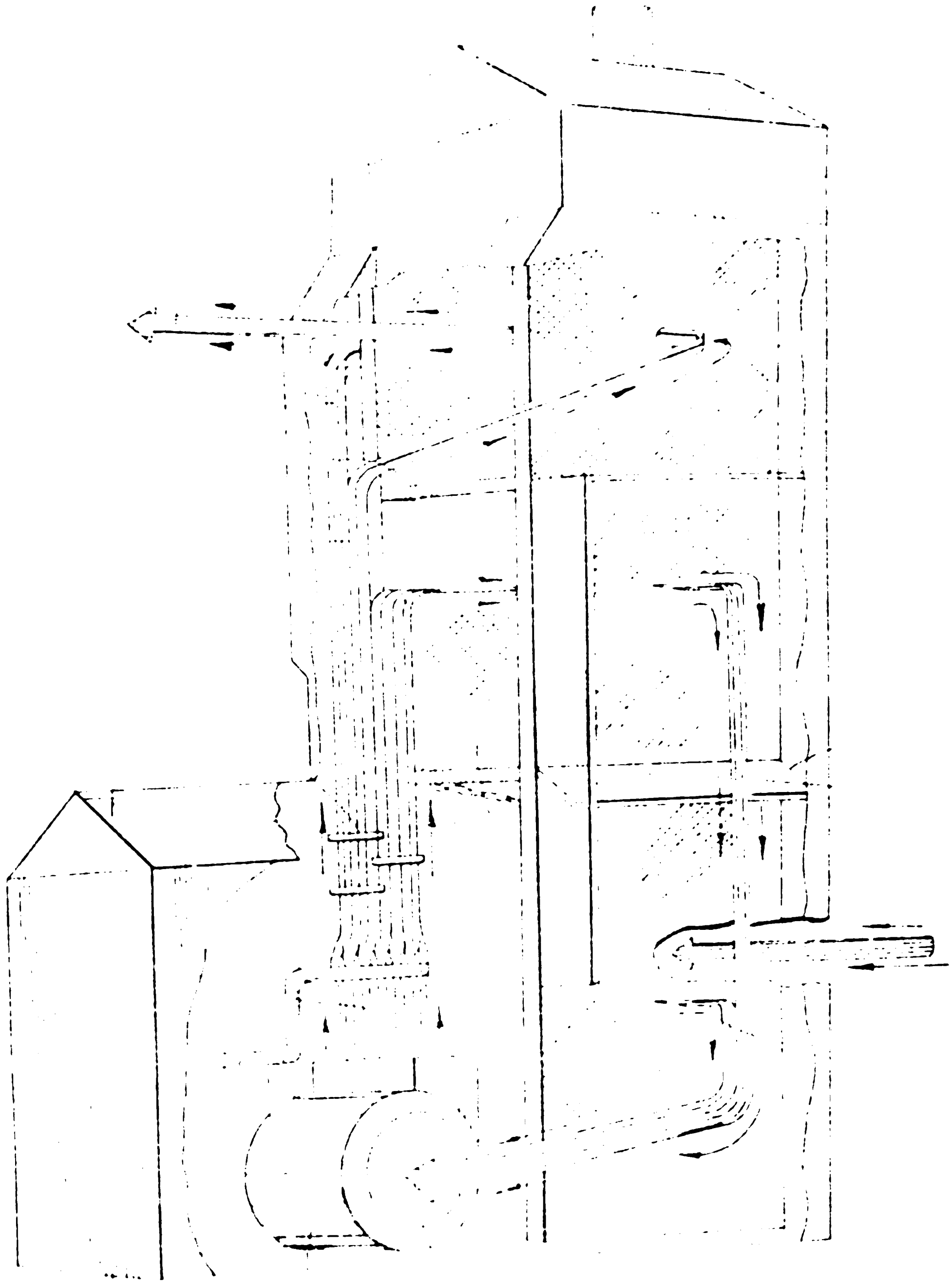


Figure 6.3. Schematic of the Hart-Carter HC-66 dryer.

Table 6.3: Dryer specifications of Hart-Carter dryer model HC-66.

Grain column length:	
first stage, ft	25.0
second stage, ft	17.0
cooling stage, ft	18.0
Total holding capacity, bu	1,728.0
in drying zone, bu	1,210.0
in cooling zone, bu	518.0
Fan horsepowerm, HP	200.0
Airflow at 3.5 in static pressure, cfm/bu	145.0
Rated drying capacity, wet bu shelled corn/hr 20% to 15%	2,070.0

carried out at Cook Farms in Salem, KY, and the last two at Toohey Farms in Lucan, Ontario, Canada during September and November of 1981, respectively.

Using corn at different initial moisture contents, the dryer output was varied to give approximately a constant outlet moisture content. The performance characteristics of the dryer were measured separately for each run. A computer drying model (Schisler, 1982) was used to analyze the results (Appendix A).

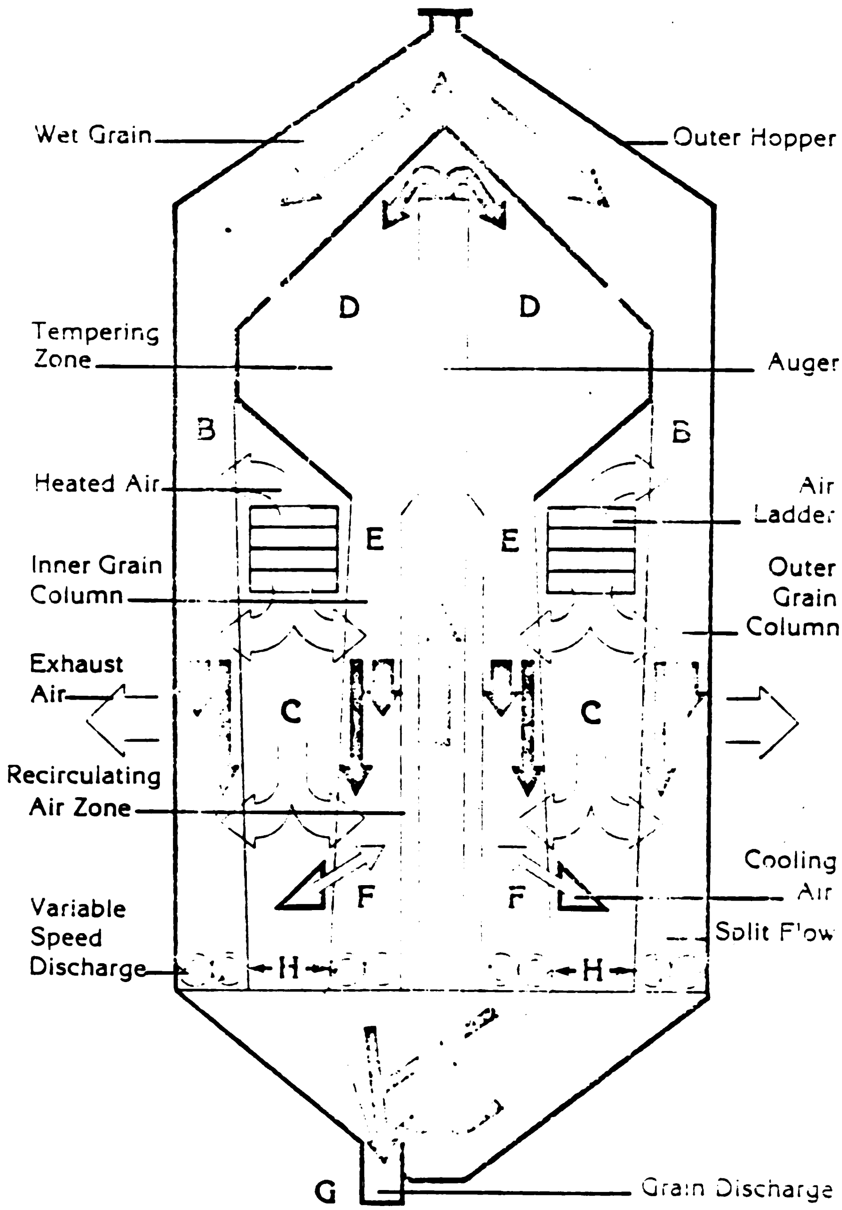
The 10-60 Blount Dryer is a unique continuous cross-flow dryer. The grain flows from a wet grain garner bin through a first set of split tapered columns (12 in. wide at the top and 16 in. wide at the bottom) to dual discharge feed rolls. Subsequently the partially dried grain is mixed and conveyed to a tempering garner from where it flows through a second set of split tapered columns for final drying and cooling. The 10-60 specifications are tabulated in Table 6.4. Figure 6.4 is a schematic of the dryer.

The two metering augers can, at the bottom of each grain column, be run at different speeds, so that grain nearest to the drying air inlet moves faster than grain on the air outlet side of the column. The tested speed ratios were between 1:2 and 1:4. This design ensures that each kernel of grain receives a similar amount of energy resulting in a more uniform outlet grain moisture content

Table 6.4: Dryer specifications of Blount/MFS dryer model 10-60.

Grain column length:	
first stage, ft	12.0
second stage, ft	6.8
cooling stage, ft	1.6
Total holding capacity, bu	685.0
in drying zone, bu	350.0
in tempering zone, bu	290.0
in cooling zone, bu	45.0
Length, ft	15.1
Width, ft	10.0
Height, ft	26.0
Fan horsepower, H.P.	60.0
Airflow at 5 in. static pressure, cfm/bu	100.0
Heater capacity, BTU/hr	6,000,000.0
Rated drying capacity, wet bu shelled corn/hr 20% to 15%	600.0

Source: Blount/CDD Catalog, 1981.



A = Outer hopper
B = Outer grain columns
C = Heat plenums
D = Tempering hopper
E = Inner drying columns
F = Cooling zone
G = Grain outlet
H = Feed rolls

Figure 6.4. Schematic of the 10-60 dryer.

than can be obtained in conventional cross-flow dryers.

The tempering or steeping zone in the 10:60 is located between the first and second drying stages (Figure 6.4 D). Tempering equalizes the internal kernel temperature and moisture content (Sabbah, 1981), increases the moisture removal rate (Sabbah et al., 1972), and reduces the breakage susceptibility (Eman et al., 1979).

Cold air is sucked through the cooling section and mixed with exhaust air from the second drying section (plus some outside air) before being heated and blown into the heating plenums. One motor is used to drive both the drying and cooling fans.

The following are the characteristic features of the 10-60 Blount Dryer:

a. tapered grain columns for a higher air flow rate near the top of the columns;

b. split grain columns with two metering augers at the bottom of each column in order to allow two grain speeds in each grain column;

c. reclaiming of part of the sensible heat of the grain in the second drying and cooling sections; and

d. steeping (tempering) of the partially dried grain.

6.5 Ferrell-Ross CCF

Three tests were conducted on a Ferrell-Ross concurrent-flow dryer model 31212 (manufacturer Ferrell-Ross, Blount Inc., Grand Island, NE). The tests were conducted during the 1979 and 1980 falls drying seasons at the Michigan Elevator Exchange terminal, Carrollton, MI. Commercial yellow corn (varieties unknown) available at the terminal was used in the tests. A computer drying model was employed to analyze the results .

The 31212 Ferrell-Ross dryer consists of three concurrent-flow drying beds (grain and drying air flowing in the same direction) and a counter-flow cooler (grain and cooling air flowing in opposite direction). Between the first and second drying stages,

and between the second and third drying stages, the grain flows through 15-ft tempering or steeping zones. It remains in a tempering zone for approximately an hour before entering the next drying stage. Figure 6.5 shows an schematic drawing of a two-stage concurrent-flow dryer.

The critical part in any concurrent-flow dryer is the hot air inlet (Westelaken and Bakker-Arkema, 1978). The very warm air has to be mixed properly and uniformly with the wet, cold grain, exposing each grain kernel for a

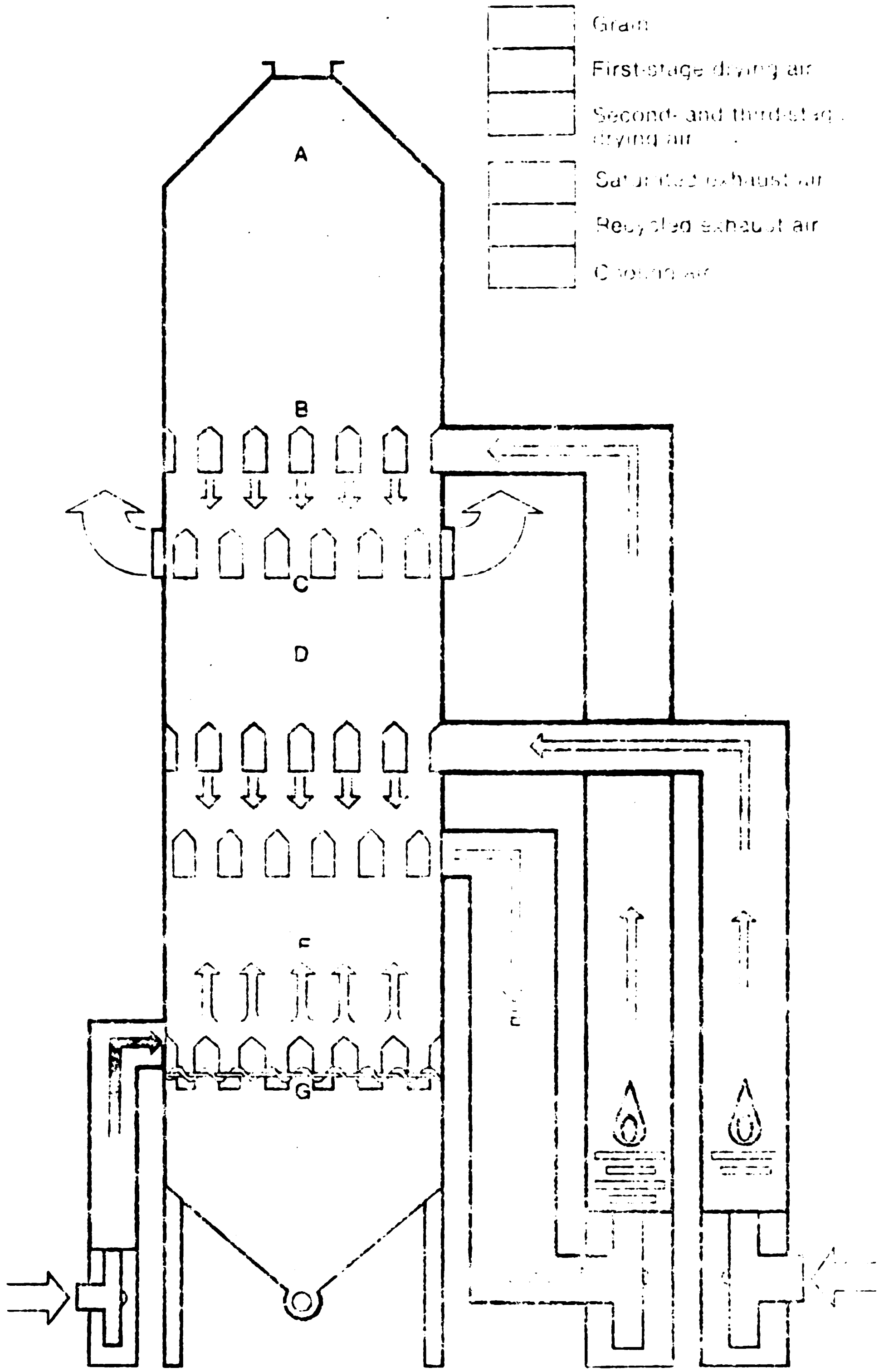


Figure 6.5. Schematic of a continuous flow two-stage concurrent-flow dryer (Ferrell-Ross CCF).

constant period (generally not exceeding 10-25 seconds) to a high temperature. The patented "Westlaken Drying Floor" (Figure 6.6) allows the heated air and wet grain to mix perfectly for uniform drying.

Wet grain enters at the top of the dryer where it forms a deep bed directly above the heat floor. Grain flows through the dryer by gravity; the flow rate is determined by the speed of rotation of the metering rolls (Figure 6.5G).

The high inlet air temperature (up to 550 F for shelled corn) decreases rapidly as the first moisture from the wet grain is evaporated. The last part of the drying bed acts as a tempering zone where moisture evaporation proceeds at a slow rate as the grain and air continue to slowly cool (Figure 4.6).

The hot grain is cooled in a counter-flow cooler. Counter-flow cooling is more efficient than cross-flow cooling. Also, the grain is not subjected in a concurrent-flow dryer to sudden chilling which causes stress cracks.

The drying air temperatures in multi-stage units decrease from the first to the second and to the third stage (Table 6.5) in order to protect the dryer grain from being overheated.

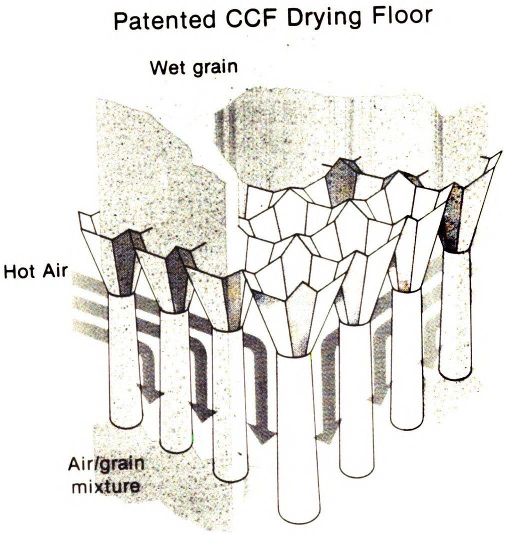


Figure 6.6. Schematic of the patented Westelaken Drying Floor.

Table 6.5 . Recommended drying air temperatures in multi-stage concurrent-flow dryers for different crops (Blount, 1980).

PLENUM TEMPERATURES v.s. DRYER DISCHARGE RATES										Grain drying/tempering retention time	
Grain	No. of Stages	Points Removed	Discharge R.P.M.	Dryer Stages Top		Mid		Btm		HOURS MAX.	MIN.
C	3	10	35/45	550°F	288°C	475°F	246°C	375°F	190°C	5.20	4.04
O	3	5	50/60	500°F	260°C	400°F	205°C	300°F	[illegible]	3.64	3.03
R	2	10	20/30	500°F	260°C			350°F	178°C	6.50	4.33
N	2	5	40/50	475°F	246°C			350°F	178°C	3.24	2.44
R	3	10	30/40	375°F	190°C	300°F	149°C	225°F	112°C	6.07	4.33
I	3	5	50/60	375°F	190°C	275°F	135°C	200°F	93°C	3.64	3.03
C	2	10	20/30	350°F	178°C			225°F	112°C	6.83	4.33
E	2	5	35/45	350°F	178°C			225°F	112°C	3.90	3.03
W	3	10	20/30	425°F	223°C	325°F	163°C	225°F	112°C	9.11	6.07
H	3	5	45/55	375°F	190°C	300°F	149°C	200°F	93°C	4.04	3.32
E	2	5	25/35	350°F	178°C			275°F	135°C	5.46	3.90
A	2	3	45/55	375°F	190°C			200°F	93°C	3.03	2.49
T	1	3	25/35	375°F	190°C					3.64	2.60

Source: Blount/Ferrell-Ross. Information Bulletin January, 1980.

6.6 Instrumentation and Procedure

- The following parameters were utilized in the performance evaluation of the dryers tested:

a. the grain moisture content before and after drying;

b. the grain initial and final temperature;

c. the grain initial and final test weight;

d. the grain initial and final quality as determined by BCFM, resistance to breakage, and burned kernels;

e. the drying capacity-dry bushels per hour;

f. the ambient and drying air temperatures and relative humidities;

g. the air flow rate; and

h. the energy consumption (heating fuel and electricity).

The approximate grain moisture content was determined during the drying operations at the test site with a "Motomco" moisture meter. Each sample was later checked by oven drying at 217 F for 72 hours (Brooker et al., 1974). Samples were collected before and after drying every half-hour during the tests. The samples were sealed in plastic bags and stored at 40 F for later analysis.

The airflows were calculated from measured static pressure data and fan curves supplied by the fan manufacturers. The data was checked against standard ASAE static pressure data (ASAE yearbook, 1981).

The temperatures were measured with copper-constantan thermocouples and whenever possible recorded with a Texas Instrument datalogger. Relative humidities were determined from dry and wet bulb temperatures.

The breakage susceptibility tests were conducted at the USDA Grain Marketing Laboratory, Manhattan, KS, employing the procedure developed by Miller et al. (1979).

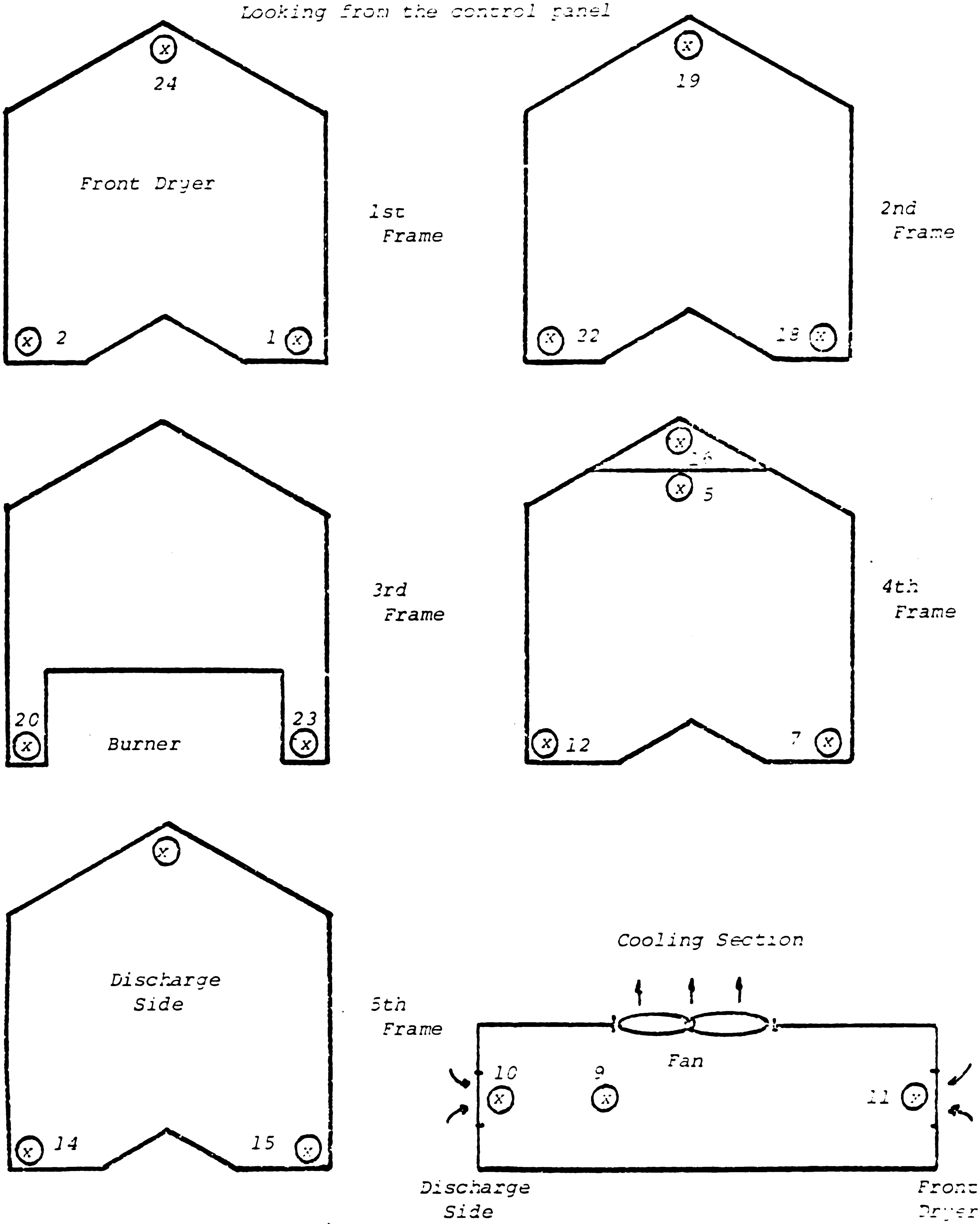
The electricity consumption was measured with kwh-meters supplied by the local electric power company.

Data taking for each test did not start before steady state had been reached in the dryer output.

6.6.1 Redex RX-10

Seventeen thermocouples were located in the heating section and four in the cooling section (Figure 6.7). After the first test (10/16/80), some thermocouples were

Looking from the control panel



Thermocouple #3 was outside of the dryer for ambient readings.

Figure 6.7. Thermocouple locations in the RX-10 dryer.

relocated in order to locate the hot spots in the dryer which were producing burned kernels. To reduce the number of burned kernels, two metal shields were installed.

The drying capacity was determined by observing the time required to fill one-half bushel with grain. The average time for five observations was used to calculate the grain flow rate and hence the drying capacity. The observations were recorded every half-hour and averaged to give the average drying capacity.

The liquid propane usage was estimated by observing the percentage readings on the LP tank gauge (and by checking these figures against the propane supply tickets)*.

Table 6.6 lists the wet corn characteristics and the drying test conditions. The initial grain moisture content of the corn varied from 34.5 to 25.6 percent w.b. and the initial test weight from 49.8 to 53.0 lb/bu. The corn was cleaned in a rotary cleaner before drying. The drying inlet air temperature varied from 186 F to 200 F.

---

* Accuracy of propane measurement +/- 5 percent.

Table 6.6: Drying conditions during the testing of the RX-10 dryer.

Wet Corn Parameters:	
Moisture content, % w.b.	25.7 to 34.5
BCFM, %	0.3 to 0.9
Test weight, lb/bu	49.8 to 53
Temperature, F	35 to 48
Air Parameters:	
Ambient temperature, F	35 to 52
Ambient relative humidity, %	60 to 100
Drying air temperature, F	185 to 205
Temp. increase through cooler, F	12 to 18
Static pressure, in	1.8 to 2.0

6.6.2 Hart-Carter HC-66

The dry bushel drying capacity was determined by observing the time required to fill a silo and weighing the dried grain. The tests lasted between 24 to 36 hours.

The drying air temperature was monitored with a mercury bulb thermometer.

The fuel consumption was measured with a calibrated gas meter. Table 6.7 lists the wet corn characteristics and the drying test conditions.

6.6.3 Blount 10-60

The grain moisture content at the outlet of each column (Figure 6.4H) was measured at different grain velocity ratios.

The dry bushel drying capacity was determined by observing the time required to fill a truck and weighing the truck with and without the grain.

The liquid propane usage was measured with a calibrated gas meter during each of the tests; the readings were multiplied by the appropriate correction factors.

Table 6.7: Drying conditions during the testing of the HC-66 dryer.

Wet Corn Parameters:	
Moisture content, % w.b.	26.9 to 29.0
Test weight, lb/bu	49.9 to 50.9
Temperature, F	46.0 to 47.0
Air Parameters:	
Ambient temperature, F	33.0 to 34.0
Ambient relative humidity, %	75.0 to 95.0
Drying air temperature, F	205.0 to 210.0

Table 6.8 lists the wet corn characteristics and the drying test conditions.

6.6.4 Ferrell-Ross CCF

The drying air temperature and grain temperatures, were monitored continuously with a potentiometer.

The gas consumption was measured with recently calibrated flow meter.

The dry bushel drying capacity was determined by observing the time required to fill a silo and weighing the dried grain. The tests lasted between 24 to 36 hours. Table 6.9 lists the wet corn characteristics and the drying test conditions.

Table 6.8: Drying conditions during the testing of the Blount 10-60 dryer.

Wet Corn Parameters:	
Moisture content, % w.b.	20.5 to 28.1
BCFM, %	0.8 to 1.5
Test weight, lb/bu	50.0 to 58.2
Temperature, F	46.0 to 97.0
Air Parameters:	
Ambient temperature, F	35.0 to 77.5
Ambient relative humidity, %	60 to 100
Drying air temperature, F	195 to 220
Temperature increase through cooler and second stage, F	16 to 50

Table 6.9 : Drying conditions during the testing of the Blount CCF-3-12-12 dryer.

Wet Corn Parameters:	
Moisture content, % w.b.	24.5 to 26.5
Test weight, lb/bu	50.2 to 50.9
Temperature, F	48.0 to 70.0
Air Parameters:	
Ambient temperature, F	33.0 to 35.0
Ambient relative humidity, %	73.0 to 97.0
Drying air temperature, F	
first stage	500.0 to 550.0
second stage	450.0
third stage	350.0

CHAPTER 7

RESULTS AND DISCUSSION

7.1 Experimental Results

The experimental results of the drying tests conducted with the four cross-flow dryers and with the concurrent-flow dryer are tabulated in Tables 7.1.1 through 7.1.5.

7.1.1 Automatic Batch

The data of nine (9) experimental tests conducted with the Farm Fans AB-8B automatic batch dryer are given in Table 7.1.1. The experimental conditions are found in Silva (1980).

Table 7.1.1: Actual energy consumption and corn quality parameters of the Farm Fans AB-8B, 1978 Drying season; drying air temperature 195 F.

TEST No.	Moisture content (% w.b.) IN	OUT	Test weight (lb/bu) IN	OUT	Energy efficiency including cooling (BTU/lb)	stress-cracks (1) (%)
1	28.4	22.9	52.0	54.0	2,069	4.6
2	28.6	22.9	52.0	54.0	2,446	4.2
3	27.9	23.0	53.0	53.7	2,243	3.7
4	26.9	22.9	53.6	54.2	2,877	4.0
5	24.7	22.7	53.3	52.7	2,838	1.5
6	24.0	20.0	53.5	53.9	2,630	8.9
7	24.8	23.5	54.3	53.5	2,148	2.9
8	26.0	15.5	54.0	55.0	2,830	87.3
9	35.7	18.3	50.0	55.5	2,238	76.0

(1) Initial stress-cracks percentage equals zero.

Source: Silva (1980)

In test no. 8 the corn was dried directly to a safe storage moisture content of 15.5 percent w.b. The corn in the other tests was dried to the intermediate moisture content of 18.0 - 23.5% as part of the combination drying process.

The principal conclusions to be drawn from the experimental data in Table 7.1.1 are:

a. the energy efficiency of a batch type dryer is dependant on the final moisture content and the number of points of moisture removed;

b. the energy efficiency of the Farm Fans automatic batch dryer in removing about ten points of moisture from 26.0 to 15.5% is approximately 2830 BTU/lb of moisture removed;

c. the grain quality deterioration in an automatic batch dryer is highly affected by the final moisture content and the degree of immediate cooling of the grain; drying to 18.0% moisture content without rapid cooling does not affect the grain quality; drying at high temperatures through the 18.5 - 15.5 moisture content range followed by immediate cooling drastically increases the number of stress-cracks and thus, the breakage susceptibility of the dried grain.

7.1.2 Continuous Flow Cross-flow With Cooling-Air Recirculation

The data of seven (7) experimental tests conducted with the Redex RX-10 continuous flow cross-flow dryer with cooling-air recirculation are tabulated in Table 7.1.2. The experimental conditions are listed in Table 6.6. In tests 6 and 7 the corn was dried immediately to a safe moisture content level below 15.5%, in the other tests the corn was removed from the dryer at an intermediate moisture content for final drying in a bin under low airflow conditions.

Several conclusions can be drawn from the experimental data in Table 7.1.2:

a. the energy efficiency of a continuous flow cross-flow dryer appears to be less dependant on the final moisture content and the number of points of moisture removed than the automatic batch dryer discussed in Table 7.1.1;

b. the energy efficiency of the Redex cross-flow dryer in removing ten points of moisture from about 25.0 to 15.0% is about 2200 BTU/lb of moisture removed;

c. the grain quality deterioration in the Redex cross-flow dryer is much less in drying to 17.0%

Table 7.1.2: Actual capacity energy consumption, and corn quality parameters of the RX-10 drying corn at 200 F, 1980 drying season.

TEST	Moisture content (% w.b.)		Test weight (lb/bu)		Average capacity (bu/hr)	Energy efficiency (BTU/lb)	Breakage[1] susceptibility increase (%)
	IN	OUT	IN	OUT			
1	34.5	28.2	49.8	49.6	197	2,189	18.1
2	26.3	16.7	50.2	50.7	144	2,244	29.3
3	27.8	23.8	53.0	53.4	275	2,319	13,7
4	27.7	22.9	51.7	52.5	273	2,208	14.1
5	25.6	18.5	51.7	52.7	214	2,225	29.9
6	25.7	14.6	52.0	51.8	141	2,063	37.6
7	26.2	14.4	51.1	51.3	143	1,965	31.2

[1] Moisture content at Stein breakage test determination is 8-9%, w.b.

moisture content and above than in drying to moisture contents below 17.0%.

7.1.3 Continuous Flow Cross-flow With Partial Drying Air And Cooling Air Recirculation

The data of two (2) experimental tests conducted with the Hart-Carter HC-66 continuous flow cross-flow dryer with partial drying air and cooling air recirculation are tabulated in Table 7.1.3. The experimental conditions for these tests are given in Table 6.7. Unlike the first two dryers discussed in section 7.1 (the Farm Fans and the Redex models), the HC-66 is a commercial sized dryer with a ten point moisture removal of well over 1000 bushels per hour.

The main conclusions to be drawn from the experimental data in Table 7.1.3 are:

a. the energy efficiency of the HC cross-flow dryer in removing about 15 points of moisture from 28.0 to 13.0% moisture content is about 2100 BTU/lb of moisture removed;

b. the grain quality deterioration of the HC commercial-sized cross-flow dryer appears to be similar to that of the farm-sized Redex cross-flow dryer.

Table 7.1.3: Actual capacity, energy efficiency and quality parameters of the HC-66 drying corn at 210 F, 1979 drying season.

TEST	Moisture content (% w.b.)		Test weight (lb/bu)		Average capacity (bu/hr)	Energy efficiency (BTU/lb)	Breakage[1] susceptibility increase (%)
	IN	OUT	IN	OUT			
1	29.0	13.9	49.9	51.3	1,050	1,950	17,5
2	26.9	12.2	50.9	52.2	863	2,223	28.1

1 Moisture content at Stein breakage test determination is 11-12%, w.b.

7.1.4 Continuous Flow Cross-flow With Partial Drying Air And Cooling Air-Recirculation , With Differential Grain Speeds , And With Tempering

The data of five (5) experimental tests conducted with the Blount 10-60 continuous flow cross-flow dryer with partial drying air and cooling air-recirculation, with differential grain speeds in each grain column, and with tempering are tabulated in Table 7.1.4. The experimental conditions are listed in Table 6.8. Tests 1, 2 and 3 were conducted in Kentucky at initial moisture contents around 20.5%. Tests 4 and 5 were performed in Canada at much higher initial moisture contents (about 28.0%). The capacity of the Blount 10-60 falls between the Farm Fans and the Redex on-farm dryers and the commercial-sized HC dryer.

The main conclusions to be drawn from the experimental data in Table 7.1.4 are:

a. the energy efficiency of the Blount 10-60 cross-flow dryer appears to be independant of the number of points of moisture removed from the grain;

b. the energy efficiency of the Blount 10-60

Table 7.1.4: Actual capacity, energy efficiency and quality parameters of the Blount/10-60, 1981 drying season, drying air temperatures 195-225 F.

TEST	Moisture content (% w.b.)		Test weight (lb/bu)		Average capacity (bu/hr)	Energy efficiency (BTU/lb)	Breakage[1] susceptibility increase (%)
	IN	OUT	IN	OUT			
1	20.5	15.4	56.9	57.7	528	1,603	36.4
2	20.5	14.8	58.2	59.1	495	1,544	37.2
3	20.6	14.7	56.3	56.3	584	1,744	47.8
4	28.4	11.9	50.0	52.0	131	1,842	34.4
5	28.1	12.2	50.0	52.0	189	1,506	38.6

[1] Moisture content at Stein breakage test determination is 8-9%, w.b.

cross-flow dryer appears to be about 1600 BTU/lb of water removed regardless of the initial or final moisture content of the grain;

c. the grain quality deterioration in the Blount 10-60 cross-flow dryer is larger than expected, probably due to damage caused by excessive auger friction in transporting the grain from the first to the second drying section.

7.1.5 Three Stage Concurrent-Flow

The data of three (3) experimental tests conducted with the Ferrell-Ross three-stage concurrent dryer are tabulated in Table 7.1.5. The experimental conditions are listed in Table 6.9. In two tests the corn was dried about ten percentage points, from about 26.0 to 15.0% moisture content; during the third test only seven points of moisture were removed. The capacity of the Ferrell-Ross was the largest of any of the dryer tested, about 1,600 bushels per hour at ten point removal.

The main conclusions to be drawn from the experimental data in Table 7.1.5 are:

a. the energy efficiency of the Ferrell-Ross multi-stage concurrent-flow dryer is approximately

Table 7.1.5: Actual capacity, energy efficiency and quality parameters of the Ferrell-Ross CCF 3-12-12, 1979 and 1980 drying seasons; drying air temperatures: 550-450-350 F.

TEST	Moisture content (% w.b.)		Test weight (lb/bu)		Average capacity (bu/hr)	Energy efficiency (BTU/lb)	Breakage[1] susceptibility increase (%)
	IN	OUT	IN	OUT			
1	26.2	15.5	50.2	52.2	1,552	1,605	3.8
2	26.5	14.8	50.9	51.8	1,375	1,760	9.5
3	24.5	17.4	50.5	52.2	2,431	1,270	-0.5

[1] Moisture content at Stein breakage test determination is 11-12%, w.b.

1600 BTU/lb of water removed in removing ten points of moisture;

b. the increase in grain breakage susceptibility in a concurrent-flow dryer is far less than in any cross-flow dryer and can even be negative (signifying an improvement in the susceptibility to breakage during the concurrent-flow drying process).

7.1.6 Dryer Comparison

The energy efficiency and breakage susceptibility data obtained experimentally with the five different dryers in three different states during three different harvesting seasons are summarized in Table 7.1.6. Although a direct comparison is not justified due to the different conditions encountered during the tests, certain trends appear evident.

The main conclusions that can be drawn from Table 7.1.6. are:

a. concurrent-flow drying is more efficient than cross-flow drying;

b. air recirculation in cross-flow dryers results in substantial energy savings;

Table 7.1.6: Experimental energy efficiency and quality parameters of five different dryers.

DRYER	Energy efficiency (BTU/lb)	Breakage susceptibility increase (%)
FF AB-8B	2,850 - 3,495	46.5[2]
Redex R-10	1,965 - 2,319	13.7[1] - 37.6
HC-66	1,950 - 2,223	17.5[2] - 28.1
Blount 10-60	1,506 - 1,842	34.4[1] - 47.8
Ferrell-Ross CCF	1,270 - 1,760	-0.5[2] - 9.5

[1] Moisture content at Stein breakage test determination is 8-9%, w.b.

[2] Moisture content at Stein breakage test determination is 11-12%, w.b.

c. airflow reversal in cross-flow dryers results in improved grain quality;

d. concurrent-flow dryers produce better quality corn than cross-flow dryers.

7.2 Standard Conditions For Dryer Simulation

In order to make a valid comparison between the five dryers investigated in this study, standard conditions need to be defined. Bakker-Arkema (1980) proposed standard conditions for the testing of grain dryers with respect to grain and ambient conditions (see Table 4.8). These will be used in the simulations for the comparison of the five dryers. The dryers include: (1) the Farm Fans (FF) automatic batch dryer, (2) the Redex continuous cross-flow dryer with cooling air recirculation, (3) the Hart-Carter (HC) with partial drying air and total cooling air recirculation, (4) the Blount continuous cross-flow dryer with partial drying air and total cooling air recirculation, with differential grain speed and tempering, and (5) the Ferrell-Ross three-stage concurrent-flow (CCF) dryer.

In addition to the ambient conditions plus the grain moisture contents and initial temperature, a standard hybrid factor has to be selected to make a meaningfull comparison between the dryers. In the experimental tests conducted with the Blount 10-60 in Kentucky, the test corn (see Table 7.3.1) had a hybrid factor of D-hybrid equal to 0.95 (K-hybrid 0.999). In the simulated comparisons (section 7.4) this value of the D-hybrid factor was used (rather arbitrarily) for the simulation of the five dryers.

7.3 Model Verification

Two basic grain drying simulation models were used in this investigation: (1) the cross-flow model, and (2) the concurrent-flow model. Both are described in detail in section 5.1.

The three stage concurrent-flow model was verified for corn by Brook (1977). Hence no further verification is necessary in this study to justify the use of the MSU concurrent-flow drying model.

The MSU three equation and four equation cross-flow models as developed by Bakker-Arkema et al. (1974) and Bakker-Arkema et al. (1977), respectively, have been modified by Schisler (1982). A listing of the Schisler

Table 7.3.1: Experimental and simulated results for the Blount 10-60 dryer, Salem, KY.

Dryer Parameter Value	Experimental	Simulated (1)
Drying air temperature, F	200.0	200.0
Airflow in dryer and cooler sections, cfm/bu	90.0	90.0
Static pressure, in. H_2O	2.7	2.7
D hybrid factor	– –	0.95
Feed roll speed ratio	2:1	2:1
Grain flow rate (burner side), bu/hr ft^2	28.7	28.7
Grain flow rate (exhaust side), bu/hr ft^2	14.4	14.4
Column width, in	14.0	14.0
Height first stage, ft	12.0	12.0
Tempering time, hr	0.45	0.45
Height second stage, ft	6.7	6.7
Height cooler, ft	1.6	1.6
MC in, % w.b.	20.5	20.5
MCout cooler, % w.b.	15.4	15.4
Grain temp. out cooler, F	– –	
Specific energy consumption, BTU/lb	1,603.0	1,579.0
Dryer efficiency factor	– –	1.015

(1) 3 equation model.

versions of the MSU cross-flow dryer models are contained in Appendix A. The simulated results of the 3-equation Schisler model for the Blount 10-60 are compared with the experimental data (as obtained with this dryer in Salem, Kentucky) in Table 7.3.1.

Table 7.3.1 shows excellent agreement between the experimental and simulated outlet moisture contents for the 10-60 cross-flow dryer. The dryer operated at 200 F at a differential grain velocity ratio of 2:1 in drying corn from 20.5 to 15.4% wet basis at an energy efficiency of 1603 BTU per pound of water removed. The D-hybrid of the corn was 0.95, the dryer efficiency factor 1.02. Similar agreement between the simulated and experimental data was obtained for the other cross-flow dryers analyzed in this study (see Tables 7.3.2, 7.3.3, 7.3.4 for the FF, Redex and HC, respectively).

7.4 Dryer Simulations

In this section the five dryers investigated are compared under standard conditions in removing fifteen, ten and five points of moisture from 30.5, 25.5 and 20.5 to 15.5 +/- 0.2% wet basis. The standard conditions used in these comparisons are given in Table 7.4.1, the dryer dimensions and airflows for the different dryers can be

Table 7.3.2: Experimental and simulated results for the Farm Fans AB-8B dryer, Bellaire, MI.

Dryer Parameter Value	Experimental	Simulated[1]
Drying air temperature, F	205.0	205.0
Airflow in dryer and cooler sections, cfm/bu	150.0	150.0
Static pressure, in. H_2O	4.2	4.2
D-hybrid factor	- -	0.9
Drying time, min.	60.0	60.0
Column width, in.	12.0	12.0
Column height, ft.	5.66	5.66
Cooling time, min.	15.0	15.0
MC in., % w.b.	26.3	26.3
Grain temperature out cooler, F	68.0	45.6
MC out cooler, % w.b.	15.5	15.5
Specific energy consumption, BTU/lb	3,495.0	2,967.0
Dryer efficiency factor	- -	1.178

[1] 3 equation model.

Table 7.3.3: Experimental and simulated results for the Redex RX-10 dryer, Bellaire, MI.

Dryer Parameter Values	Experimental	Simulated[1]
Drying air temperature, F	200.0	200.0
Airflow in dryer and cooler sections, cfm/bu	100.0	100.0
Static pressure, in. H_2O	2.1	2.1
D-hybrid factor	- -	0.95
Grain flow rate, bu/hr ft^2	7.7	7.7
Column width, in.	11.0	11.0
Height drying stage, ft	6.58	6.58
Height cooling stage, ft	3.29	3.29
MC in., % w.b.	25.6	25.6
MC out cooler, % w.b.	18.5	18.7
Grain temperature out cooler, F	- -	45.9
Specific energy consumption, BTU/lb	2,225	2,048
Dryer efficiency factor	- -	1.141

[1] 3 equation model.

Table 7.3.4: Experimental and simulated results for the Hart-Carter HC-66, Carrollton, MI.

Dryer Parameter Values	Experimental	Simulated[1]
Drying air temperature, F	210.0	210.0
Airflow in dryer and cooler sections, cfm/bu	145.0	145.0
Static pressure, in. H_2O	3.9	3.9
D-hybrid factor	- -	0.9
Grain flow rate, bu/hr ft^2	21.0	21.0
Column width, in.	12.0	12.0
Height first stage, ft	25.0	25.0
Height second stage, ft	17.0	17.0
Height cooling stage, ft	18.0	18.0
MC in., % w.b.	29.0	29.0
Grain temperature out cooler, F	62.0	34.8
MC out cooler, % w.b.	13.9	13.9
Specific energy consumption, BTU/lb	1,950.0	1,869.0
Dryer efficiency factor	- -	1.04

[1] 3 equation model.

Table 7.4.1: Standard conditions used in dryer comparison.

Parameter	Value
Ambient temperature, F	60.
Ambient relative humidity, %	60.
Inlet grain temperature, F	60.
BCFM, %	3.
Atmospheric pressure, in. Hg	30.

obtained from Tables 6.1 through 6.5.

7.4.1 Farm Fans AB-8B

Table 7.4.1-1 contains the data in drying corn at 20.5, 25.5 and 30.5 percent moisture content to 15.5 +/- 0.2 percent in the Farm Fans automatic batch dryer. Figures 7.4.1a, 7.4.1b, and 7.4.1c illustrate the three drying phases graphically. Some interesting observations can be made:

a. the energy efficiency in removing fifteen moisture percentage points is 27 percent better (e.g. ·802 fewer BTU's are required to remove a pound of water) than for five moisture percentage points;

b. the moisture gradient in the dried/cooled grain varies from 3.0 percent in the five point removal case to 6.6 percent in the fifteen point case (without cooling, these numbers are 4.5 and 9.3 percent, respectively).

c. the temperature gradient in the grain at the end of the drying cycle is about 30-35 F and is independant of the points of moisture removed; at the end of the cooling phase, these temperature gradients have decreased to 26 F for the 5-points

Table 7.4.1-1: The effect of initial moisture content (and grain flow rate) on the drying characteristics of the automatic batch Farm Fans AB-8B dryer at inlet air temperature of 200 F under standard conditions; final MC = 15.5% +/- 0.2%.

Parameter Values		Moisture content in (% w.b.) 20.5		Moisture content in (% w.b.) 25.5		Moisture content in (% w.b.) 30.5	
		Without cooler	With cooler	Without cooler	With cooler	Without cooler	With cooler
MC content (% w.b.)	Min.	13.6	13.6	12.8	12.9	12.0	12.1
	Ave.	15.7	15.3	15.9	15.5	16.1	15.5
	Max.	18.1	16.6	19.7	17.8	21.3	18.7
Corn temp. (F)	Min.	163.5	60.2	166.4	60.2	166.0	60.1
	Ave.	184.3	65.9	186.7	63.3	187.6	62.6
	Max.	197.7	86.9	198.3	75.2	198.6	71.6
Time in dryer (min.)		35	45	61	72	85	97
Air exhaust humidity ratio		0.0167	0.0065	0.0164	0.0063	0.0166	0.0063
RH average (out)(%)		7.46	24.00	6.86	34.27	7.01	38.44
Energy efficiency (BTU/lb)		3,815	2,976	3,115	2,546	2,677	2,174

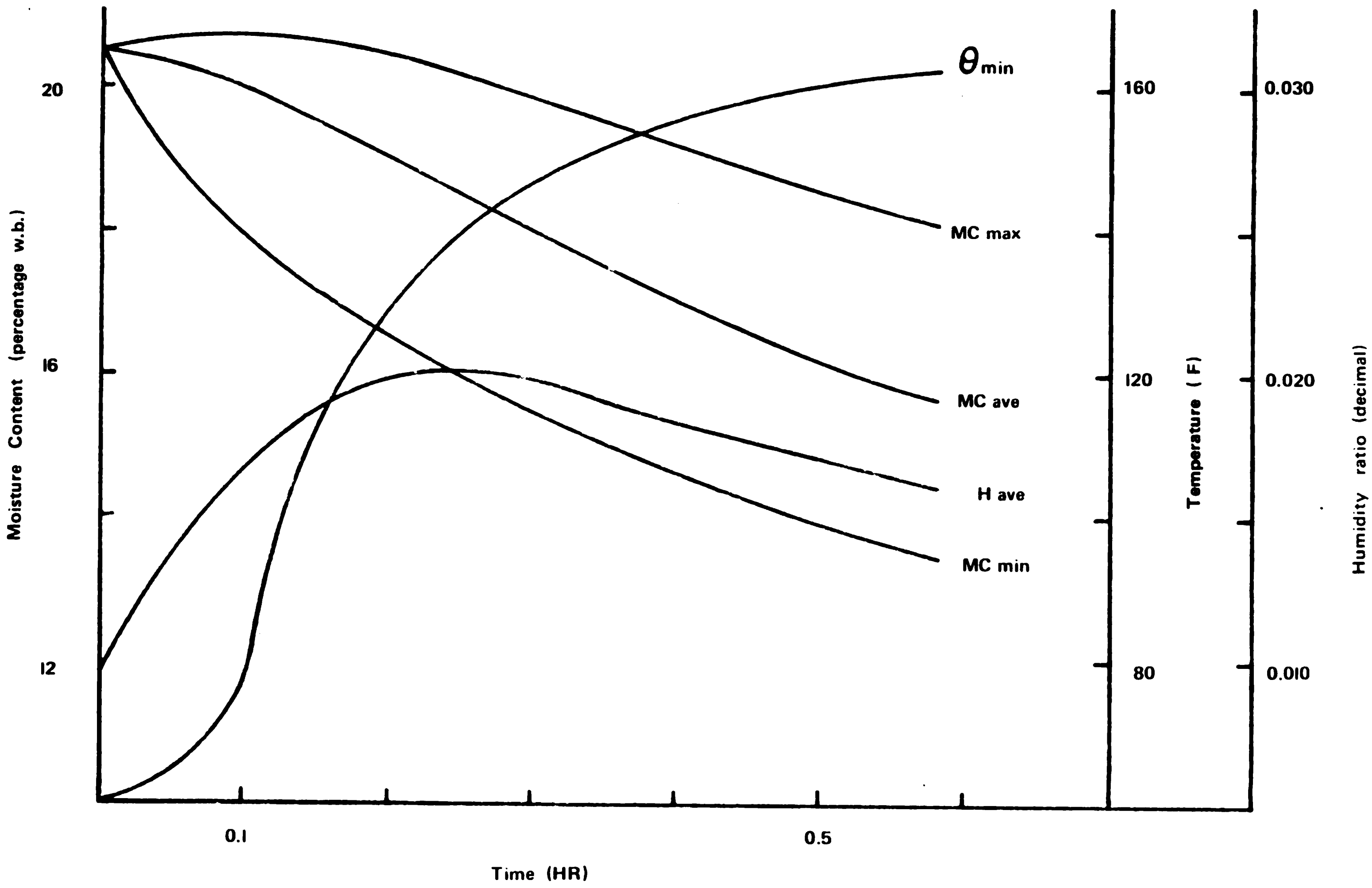


Figure 7.4.1a: Humidity ratio, kernel temperature and MC distributions of the AB-8B (initial MC = 20.5%).

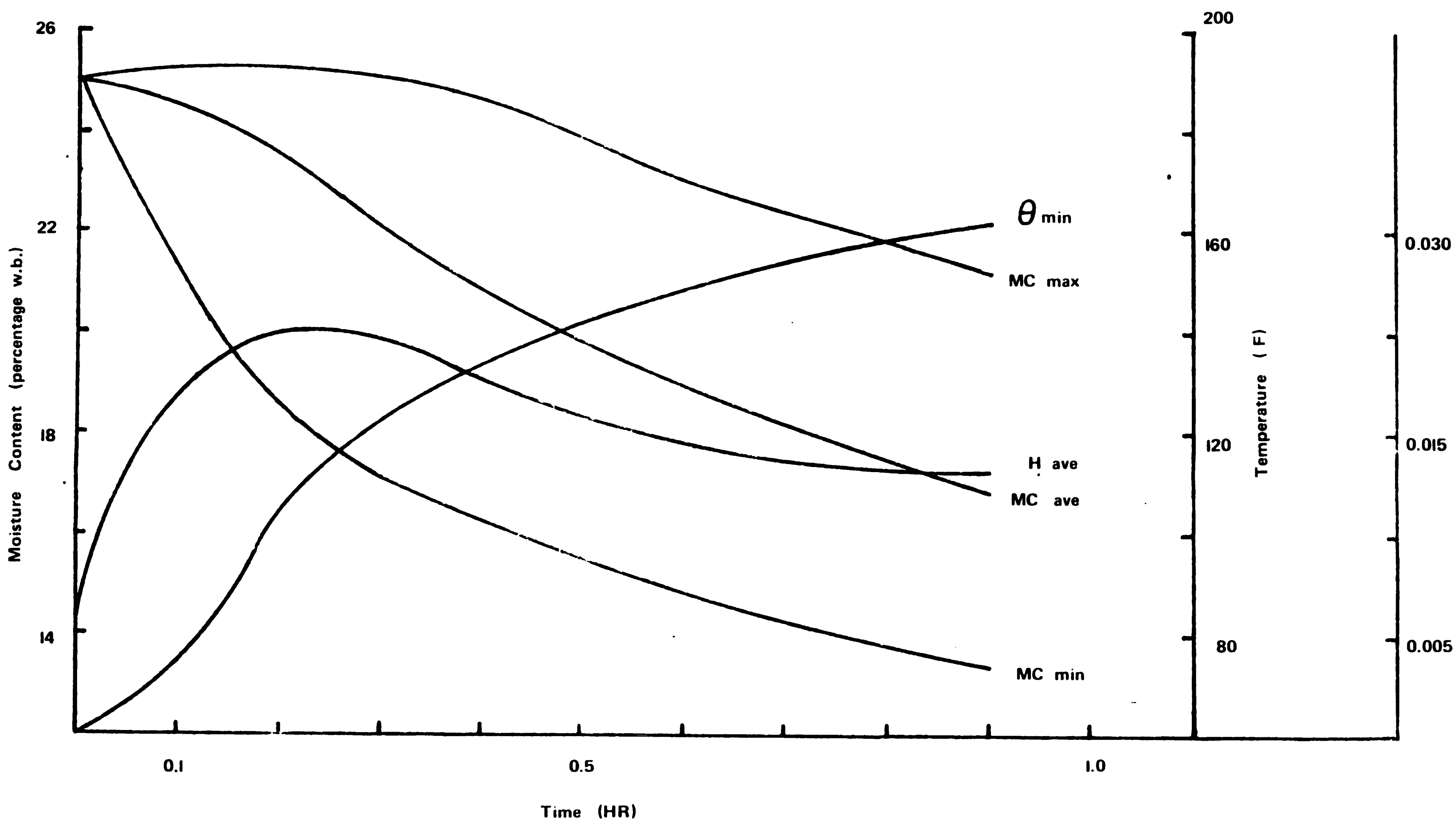


Figure 7.4.lb: Humidity ratio, kernel temperature and MC distributions of the AB-8B (initial MC = 25.5%).

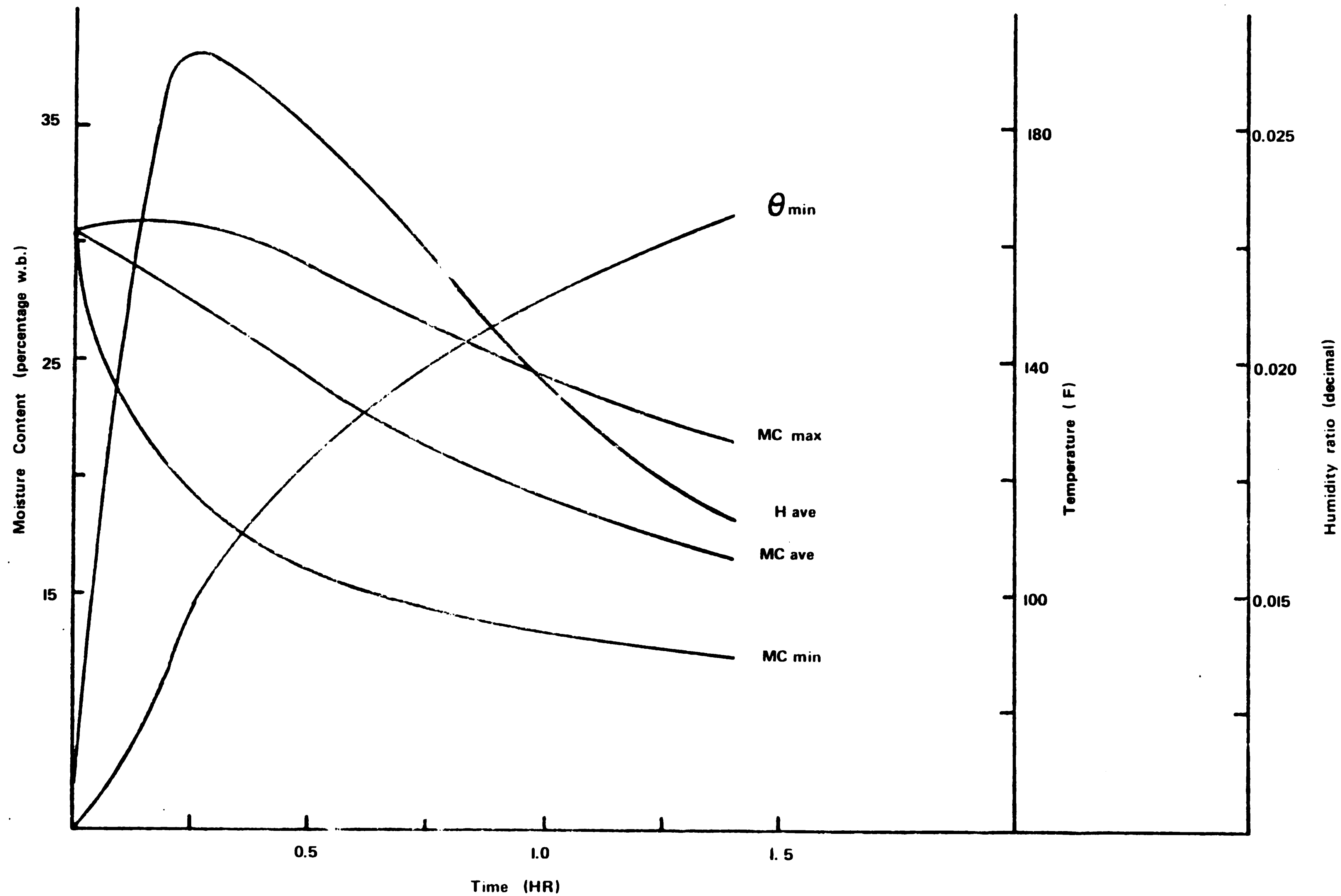


Figure 7.4.Ic: Humidity ratio, kernel temperature and MC distributions of the AB-8B (initial MC = 30.5%).

removal and to 11 F for the 15-points removal dryer;

d. at the end of the drying cycle the humidity ratio and the relative humidity of the exhaust air are independent of the points of moisture removed (e.g. 0.0166 and 7%, respectively, for all three cases considered;

e. the absolute humidity of the exhaust air is on the order of 0.010 to 0.025 with the higher values occuring in the 15-point removal drying process.

7.4.2 Redex RX-10

The operating data of the Redex RX-10 in drying shelled corn at 30.5, 25.5 and 20.5 percent moisture content under standard conditions to 15.5 +/- 0.2 percent is tabulated in Table 7.4.2-1. A graphical presentation of the drying characteristics of the RX-10 is given in Figures 7.4.2a, 7.4.2b, and 7.4.2c. The main conclusions to be drawn from the simulated data are:

a. the energy efficiency of the RX-10 is greatly affected by the initial moisture content of the grain (i.e. 2,879 and 2,324 BTU/lb at initial MC values of 20.5 and 30.5%, respectively); recycling

Table 7.4.2-1: The effect of initial moisture content (and grain flow rate) on the drying characteristics of the Redex RX-10 at the air inlet temperature of 200 F operating under standard conditions; final moisture content 15.5 +/- 0.2%,

Parameter Values		20.5% initial MC (% w.b.)	25.5% initial MC (% w.b.)	30.5% initial MC (% w.b.)
MC content (% w.b.)	Min.	12.8	11.8	10.7
	Ave.	15.7	15.7	15.3
	Max.	18.6	20.1	21.5
Corn temp. (F)	Min.	59.8	59.9	60.0
	Ave.	61.5	60.7	60.8
	Max.	67.3	61.9	62.0
Time in dryer (min.)		57	110	168
Air exhaust humidity ratio		0.0211[1] 0.0085[2]	0.0235[1] 0.0072[2]	0.0251[1] 0.0067[2]
RH average (out) (%)		32.5[1] 11.5[2]	30.0[1] 12.5[2]	32.0[1] 25.0[2]
Energy efficiency (BTU/lb)		2,641	2,322	2,133

1 First drying stage.

2 Cooling stage.

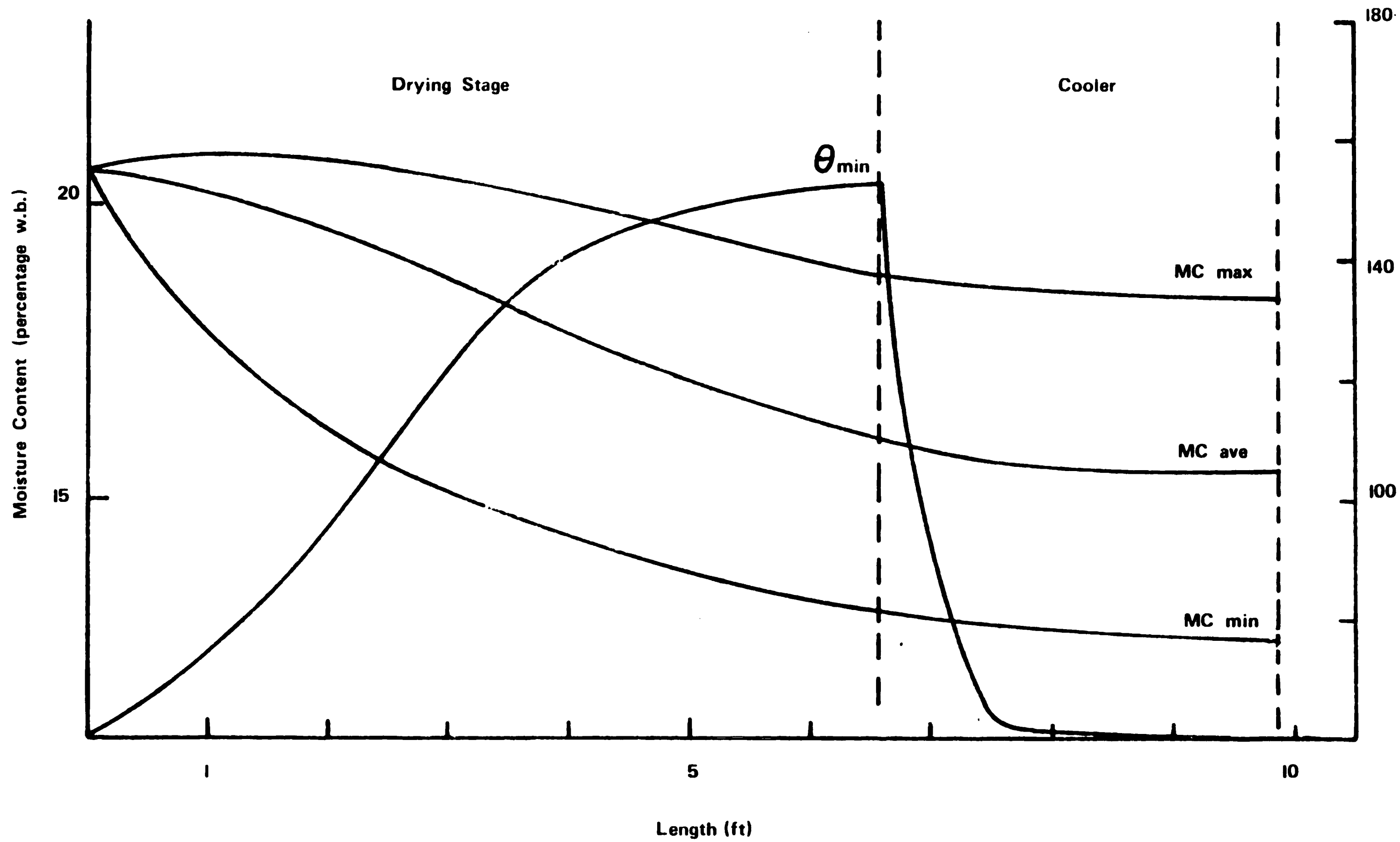


Figure 7.4.2a : Kernel temperature and MC distributions of the RX-10 (initial MC = 20.5%).

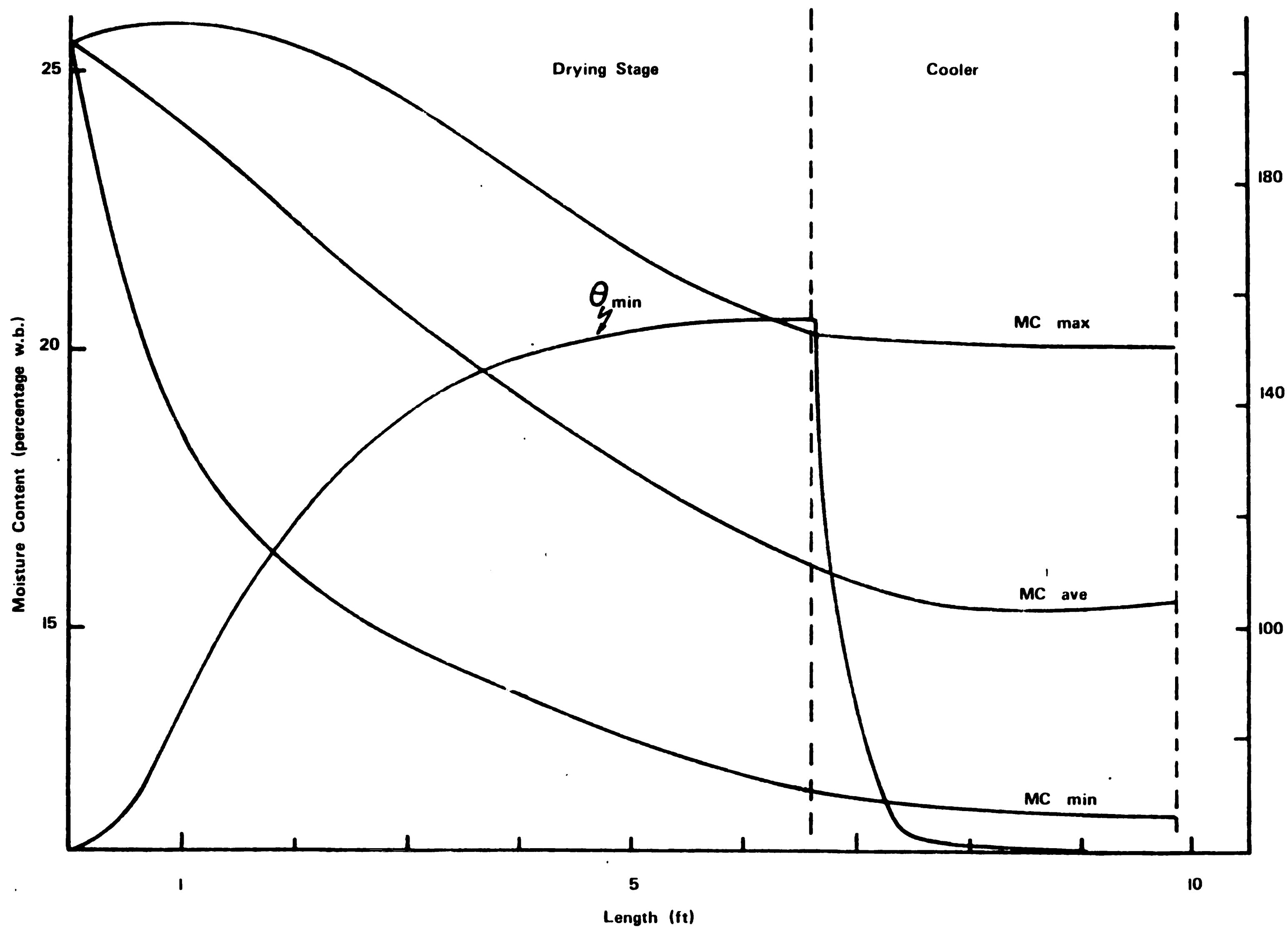


Figure 7.4.2b : Kernel temperature and MC distributions of the RX-10 (initial MC = 25.5%).

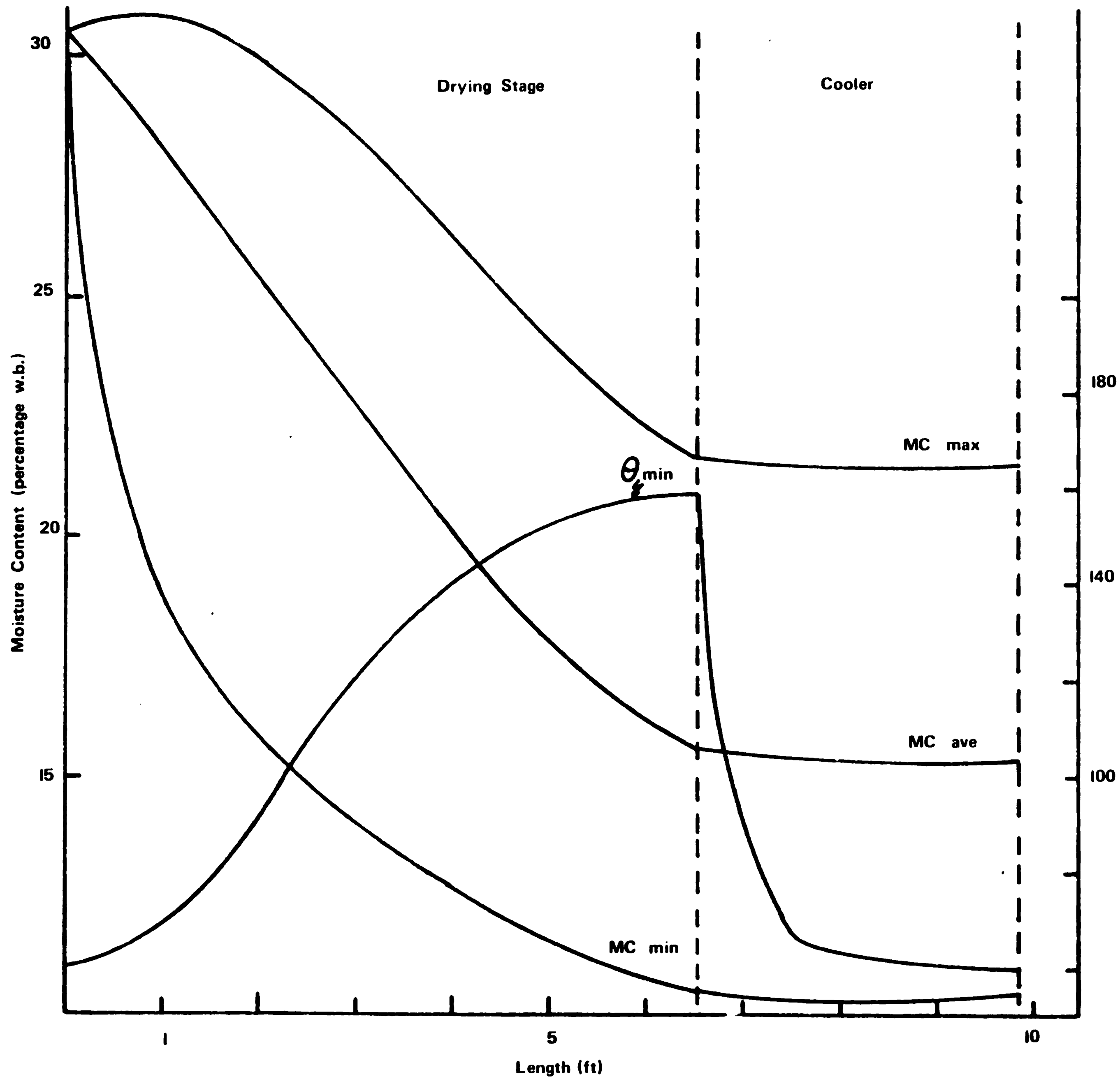


Figure 7.4.2c : Kernel temperature and MC distributions of the RX-10 (initial MC = 30.5%).

of the cooling air decreased the energy consumption compared to the Farm Fans AB-8B;

b. the final moisture gradient of the cooled grain is large (i.e. 5.8% at MC initial= 20.5% and 10.8% at 30.5%) due to the relative small airflow rate (90 cfm/bu) of the RX-10;

c. the overdrying of part of the grain at the air inlet side of the drying section is rather severe (i.e. to 10.7 percent for the case of MC initial - 30.5%);

d. the average absolute and relative humidities of the exhaust air in the dryer sectiion are relatively low due to the small thickness (11 in.) of the grain column (this dimension 12 to 14 inches in the other cross-flow dryers tested in this study);

e. the residence time in RX-10 for five points removal is about one hour; the same amount of moisture is removed in 45 minutes in the automatic batch dryer (i.e. in the Farm Fans AB-8B).

7.4.3 HC-66

The pertinent drying data of the HC-66 drying 30.5, 25.5 and 20.5 percent moisture content corn under standard conditions is presented in Table 7.4.3-1. The moisture content and temperature distributions within the dryer are shown in Figures 7.4.3a, 7.4.3b, and 7.4.3c. The following conclusions are justified:

a. the energy efficiency of the HC is better at high initial grain moistures than at lower initial values (i.e. 2,410 BTU/lb at MC initial= 20.5% and 1,752 BTU/lb at 30.5%).

b. the moisture gradient in the dried/cooled grain is relatively small due to the reversal of airflow between the first and second drying stages (i.e. 1.9% at MC initial= 20.5% and 2.6% at MC initial= 30.5%);

c. the average absolute humidity of the exhaust air is relatively high due to the

Table 7.4.3-1: The effect of initial moisture content (and grain flow rate) on the drying characteristics of the HC-66 dryer at inlet air temperature of 210 F <u>under standard conditions</u>; final moisture content 15.5 +/- 0.2%.

Parameter	Values	20.5% initial MC (% w.b.)	25.5% initial MC (% w.b.)	30.5% initial MC (% w.b.)
MC content (% w.b.)	Min. Ave. Max.	13.9 15.4 16.2	13.6 15.7 16.8	13.0 15.6 17.2
Corn temp. (F)	Min. Ave. Max.	60.1 61.7 67.9	60.1 60.7 61.5	60.2 60.7 61.5
Time in dryer (min.)		46	79	112
Air exhaust humidity ratio		0.0314[1] 0.0334[2] 0.0082[3]	0.0358[1] 0.0337[2] 0.0073[3]	0.0390[1] 0.0070[3]
RH average (out) (%)		55.0[1] 15.1[2] 7.7[3]	55.0[1] 15.2[2] 15.0[3]	62.0[1] 15.3[2] 21.0[3]
Energy efficiency		2,410	1,998	1,752

[1] First drying stage.

[2] Second drying stage.

[3] Cooling stage.

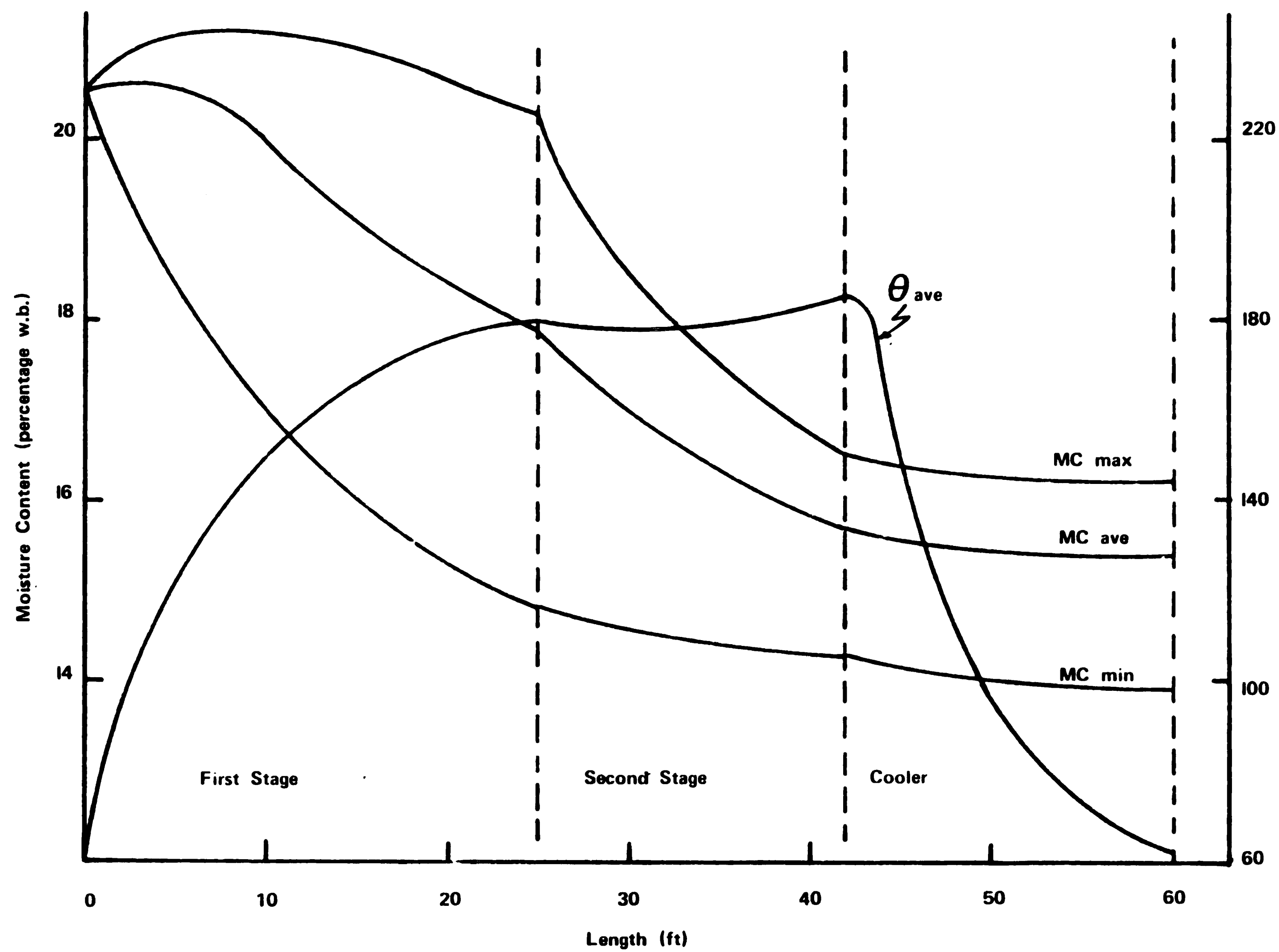


Figure 7.4.3a : Kernel temperature and MC distributions of the HC-66 (initial MC = 20.5%).

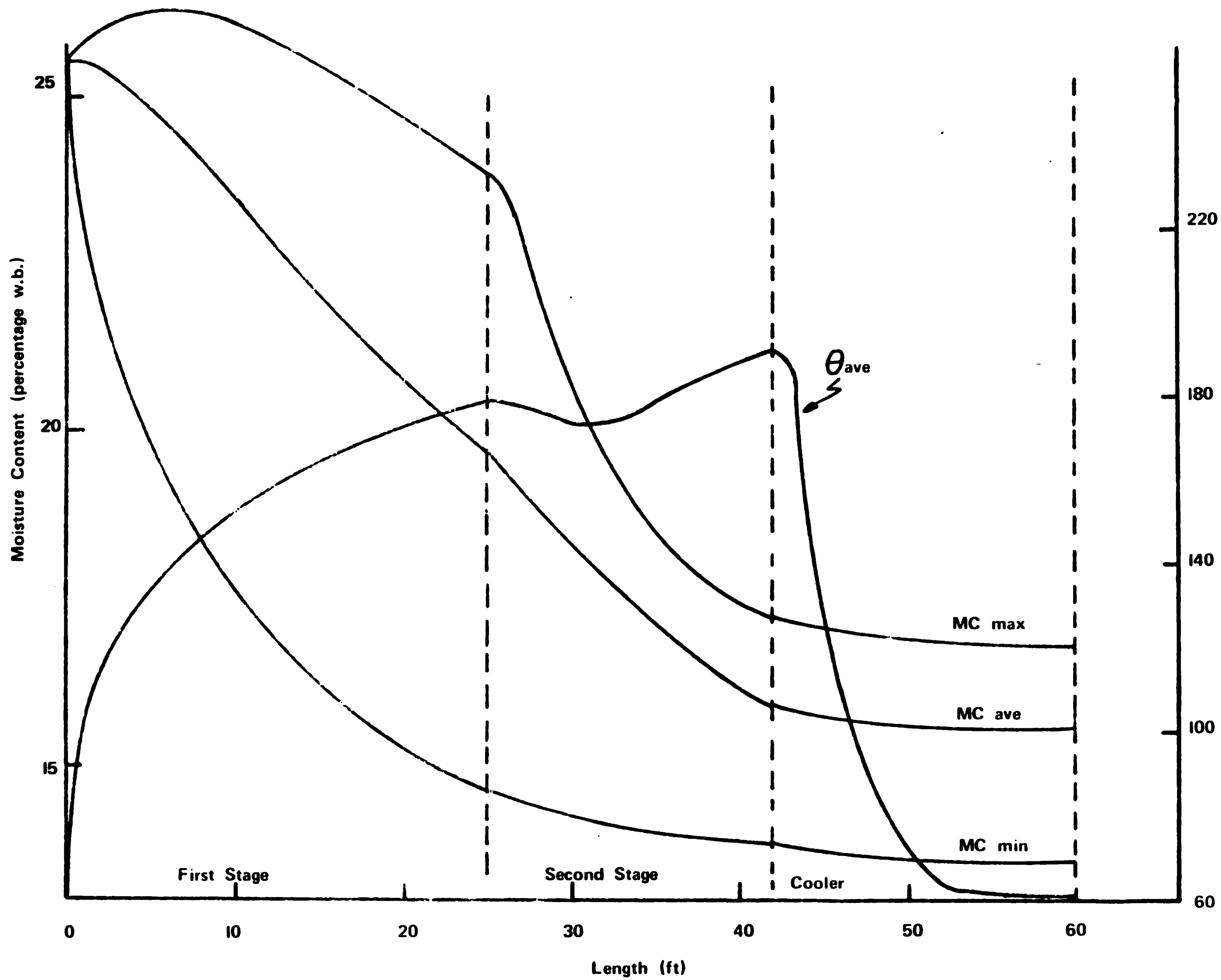


Figure 7.4.3b : Kernel temperature and MC distributions of the HC-66 (initial MC = 25.5%).

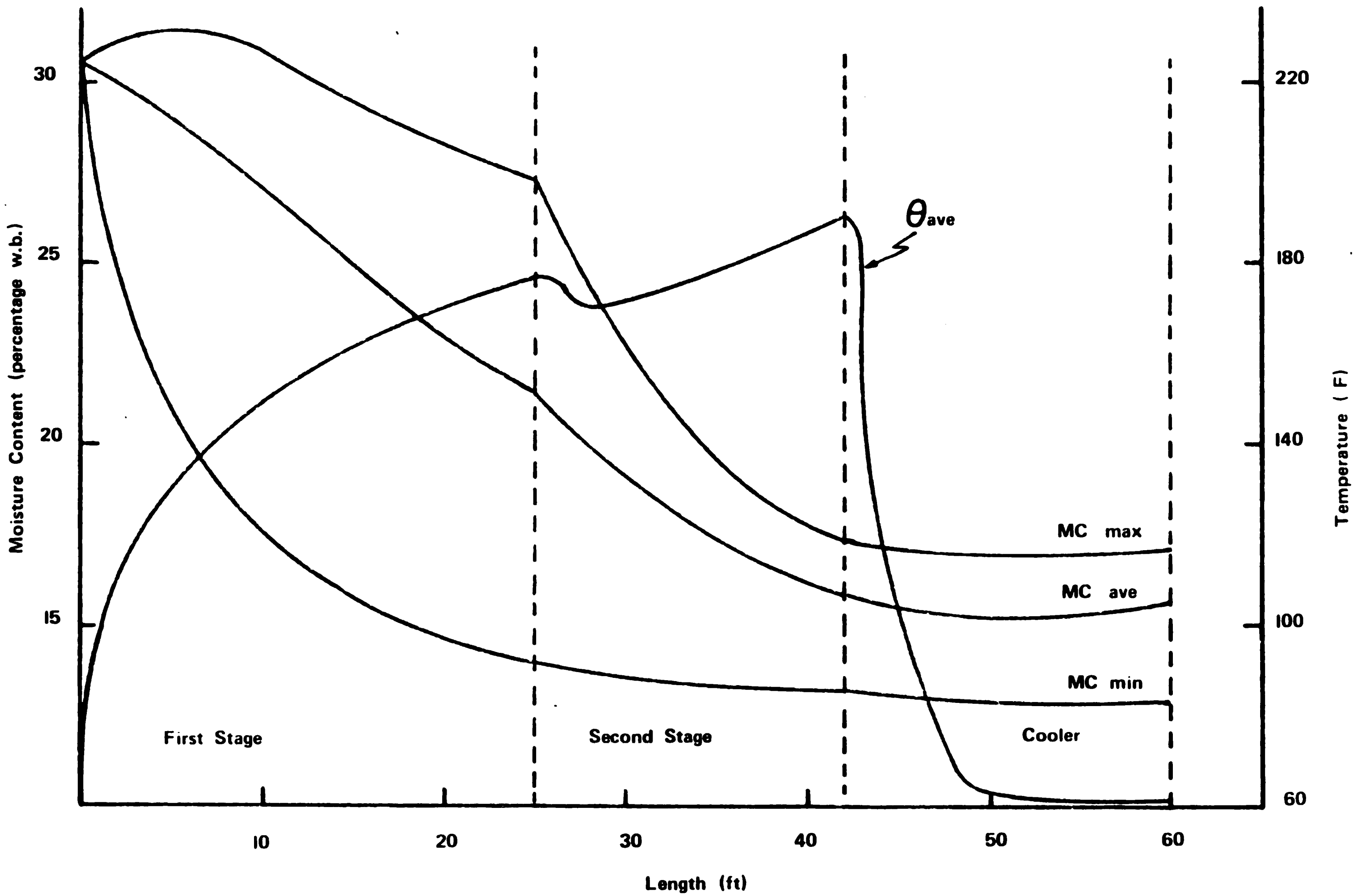


Figure 7.4.3c : Kernel temperature and MC distributions of the HC-66 (initial MC = 30.5%).

recycling of the cooling air and part of the drying air but the relative humidity is low, indicating that the airflow in the HC-66 is high (145 cfm/bu);

d. the humidity ratio of the exhaust air in the second drying stage is about the same as in the first drying stage; a surprising result since only the air from the second stage is recirculated;

e. since the corn at all three initial moisture contents is dried to the ambient temperature (i.e. 60 F), the airflow rate in the cooling section appears to be overdesigned for the removal of 10 and 15 points of moisture.

7.4.4 Blount 10-60

Table 7.4.4-1 and Figures 7.4.4a, 7.4.4b, and 7.4.4c represent the drying of 30.5, 25.5 and 20.5 percent moisture content corn to 15.5 +/- 0.2 percent in the Blount 10-60 differential grain speed continuous flow cross-flow dryer. The important observations to be made are:

a. the inlet moisture content has a relatively small effect on the energy efficiency of the dryer (e.g. 1,278 BTU/lb at 30.5% versus 1,621 BTU/lb at 20.5% inlet moisture content);

b. the moisture content gradient of the dried corn is small and varies from less than 1% in drying five moisture points to 3.2% in drying 15 points;

c. the 2:1 grain velocity ratio leads to a fairly uniform moisture content distribution across the drying column (e.g. in the 5-point case the MC values across the dryer column at the grain exit are 15.1, 15.6, 15.9, 15.0, 15.5, 16.0%, respectively);

d. the average outlet absolute humidity values in the two drying stages vary little with initial moisture content and are between 0.03 and 0.04;

e. the average corn temperature of the faster flowing grain (e.g. on the air inlet side

Table 7.4.4-1: The effect of initial moisture content (and grain flow rate) on the drying characteristics of the Blount 10-60 at the air inlet temperature of 200 F drying under standard conditions, final average MC 15.5 +/- 0.2% w.b.; grain speed ratio 1:2.

Parameter Values		20.5% initial MC (% w.b.)	25.5% initial MC (% w.b.)	30.5% initial MC (% w.b.)
MC content (% w.b.)	Min. Ave. Max.	15.0 15.6 16.0	14.0 15.5 16.6	13.3 15.4 16.5
Corn temp. (F)	Min. Ave. Max.	69.3 127.7 168.5	60.9 97.6 157.4	60.3 80.7 132.0
Time in dryer (min.)		79[1]	150[1]	212[1]
Air exhaust humidity ratio		0.0312[2] 0.0339[3] 0.0175[4]	0.0358[2] 0.0325[3] 0.0147[4]	0.0386[2] 0.0334[3] 0.0127[4]
RH average (out) (%)		60.0[2] 17.0[3] 9.5[4]	60.5[2] 18.5[3] 6.4[4]	70.0[2] 19.0[3] 6.5[4]
Energy efficiency (BTU/1b)		1,621	1,435	1,278

[1] Average time.

[2] First drying stage.

[3] Second drying stage.

[4] Cooling stage.

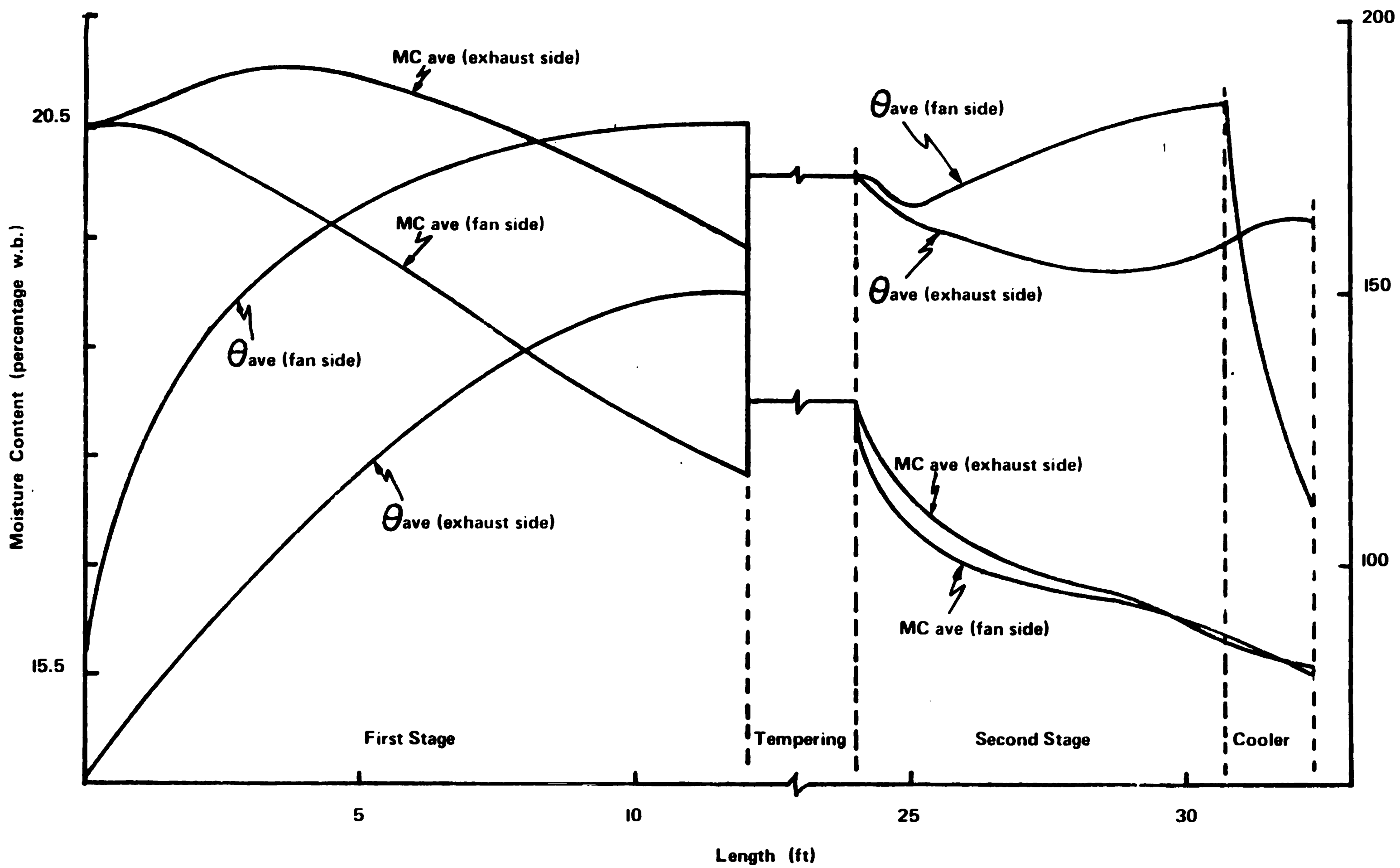


Figure 7.4.4a : Moisture content and kernel temperature distributions of the Blount 10-60 (initial MC = 20.5%).

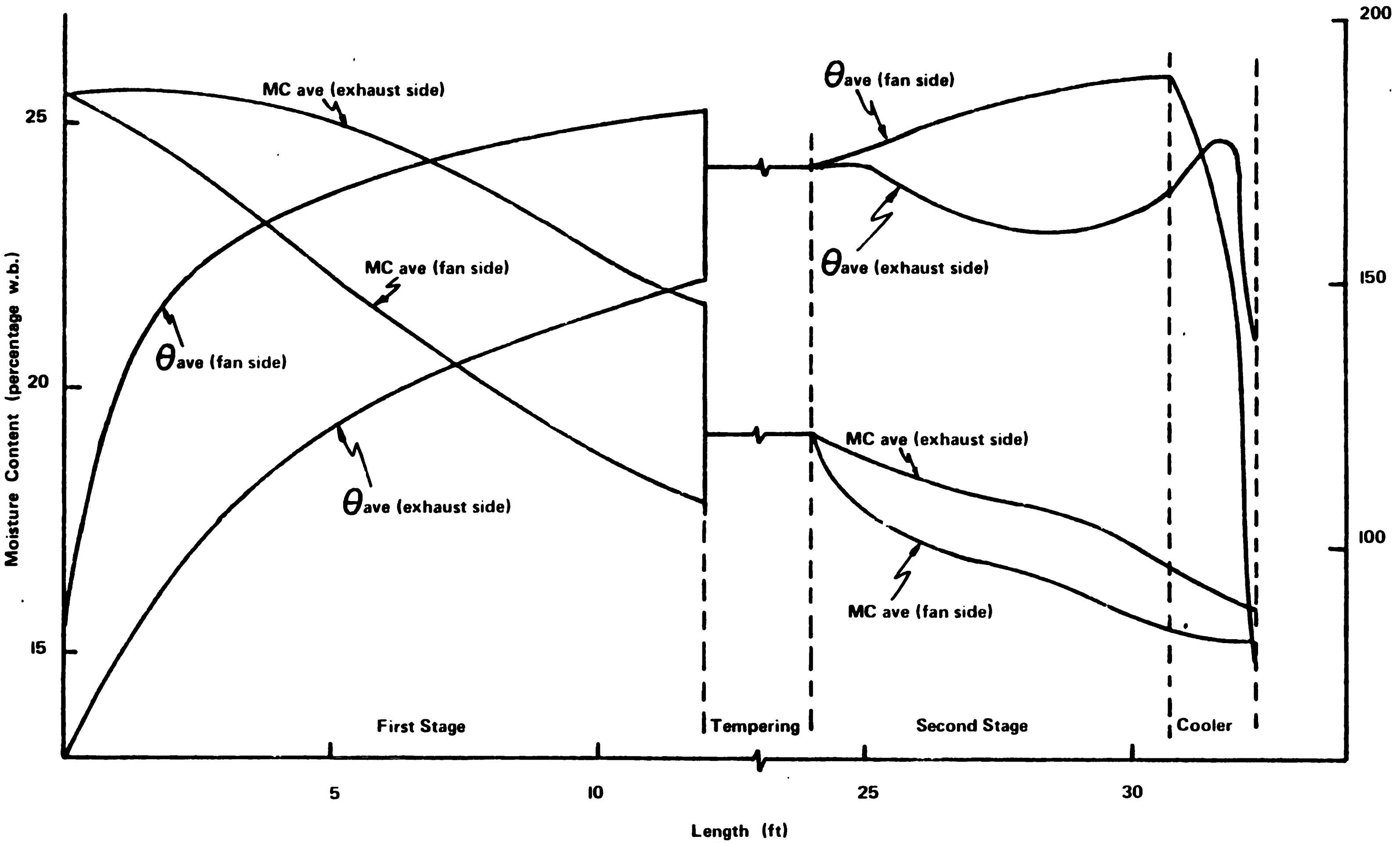


Figure 7.4.4b : Moisture content and kernel temperature distributions of the Blount 10-60 (initial MC = 25.5%).

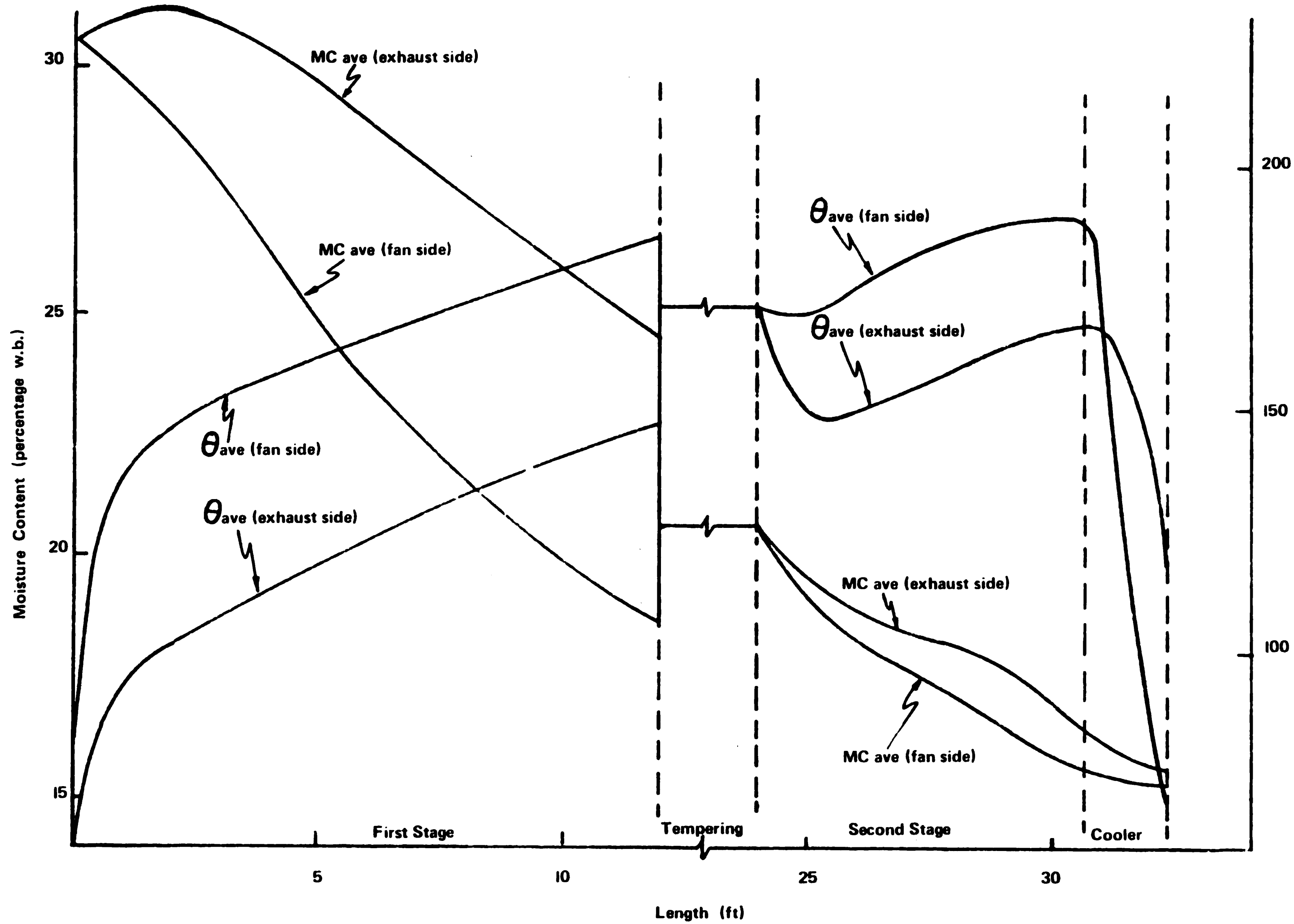


Figure 7.4.4c : Moisture content and kernel temperature distributions of the Blount 10-60 (initial MC = 30.5%).

of a column) is about 180-190 F regardless of the number of points of moisture removed, and is about 150-170 F for the slower flowing corn at the air exhaust side;

f. the cooler for the 10-60 is underdesigned especially for the case of five point moisture removal.

7.4.5 Ferrell-Ross CCF

Table 7.4.5-1 and Figures 7.4.5a, 7.4.5b, and 7.4.5c contain the relevant simulation results in drying 30.0, 25.5 and 20.5 percent moisture content corn to 15.5 +/- 0.2 percent in a Ferrell-Ross CCF three-stage concurrent-flow dryer. Some interesting points can be observed:

a. the inlet moisture content has a large effect on the energy efficiency; removing 5 percentage points requires almost 23 percent more energy than drying fifteen points of moisture;

b. the outlet grain temperature in the three stages is a function of the initial

Table 7.4.5-1: The effect of initial moisture content (and grain flow rate) on the operating conditions of the three stage Ferrell-Ross CCF concurrent flow dryer at inlet air temperatures of 550-450-350 F under standard conditions.

Parameter Values	G_p=21.0 bu/hr ft^2 M(in) = 20.5%	G_p=11.5 bu/hr ft^2 M(in) = 25.5%	G_p=8.0 bu/hr ft^2 M(in) = 30.0%
Stage 1			
M(out),%	19.4	22.7	25.8
(out), F	112.3	110.6	108.5
H(out)	.0404	.0609	.0703
RH(out),%	64.5	98.7	100.0
Stage 2			
M(out),%	17.6	18.7	20.2
(out), F	133.9	122.6	116.7
H(out)	.0507	.0647	.0688
RH(out),%	44.1	74.3	92.5
Stage 3			
M(out),%	16.2	16.1	16.2
(out), F	133.6	123.1	114.9
H(out)	.0471	.0486	.0512
RH(out),%	41.5	56.6	74.4
Cooler			
M(out),%	15.6	15.5	15.5
(out), F	104.9	88.4	77.4
H(out)	.0249	.0172	.0141
RH(out),%	50.4	58.2	68.5
Grain speed (ft/hr)	30.4	16.6	11.6
Energy efficiency (BTU/lb)	1,921	1,591	1,487
Time in dryer	102	186	268

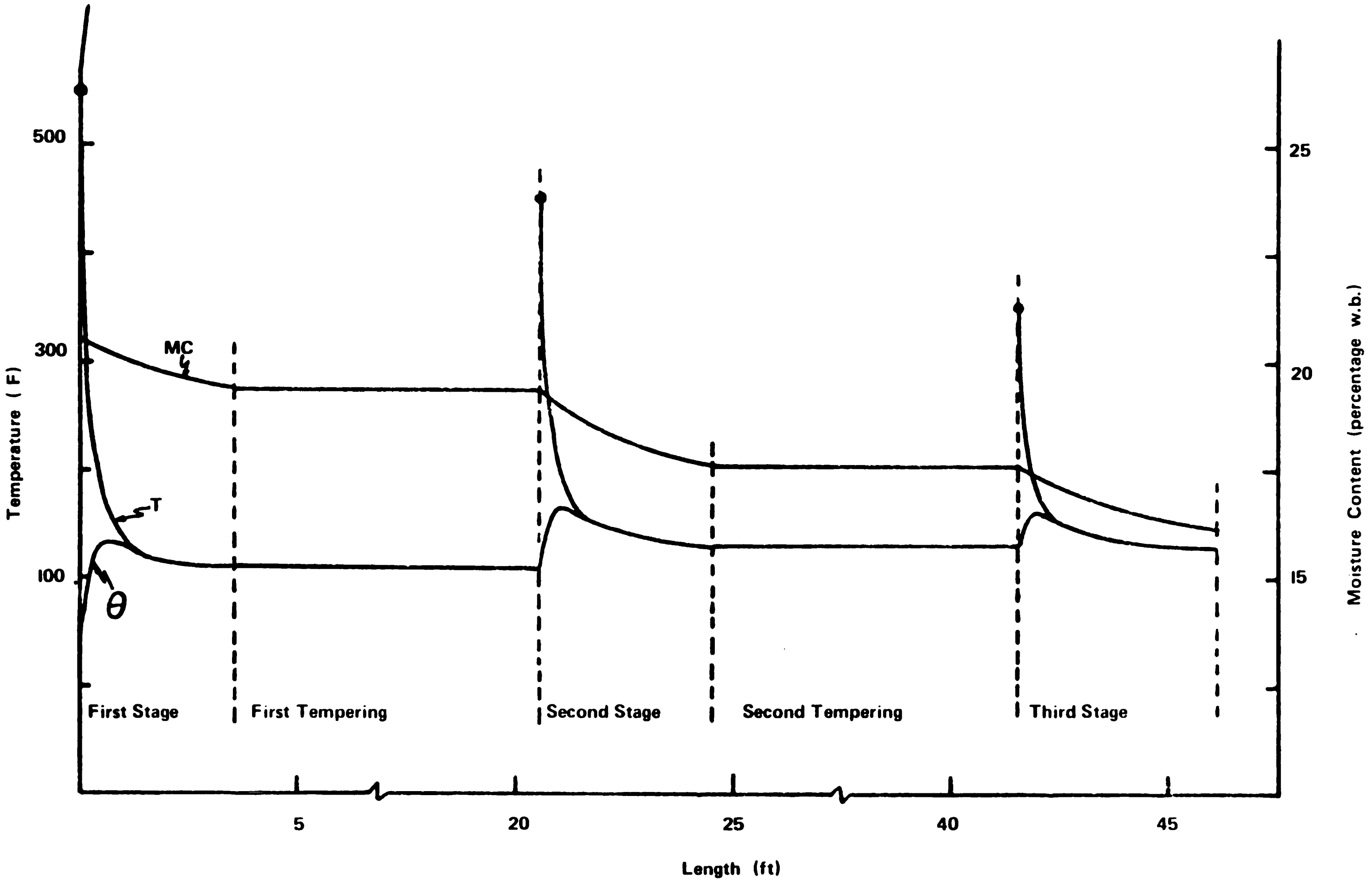


Figure 7.4.5a : Air and kernel temperatures and MC distributions in the CCF (initial MC = 20.5%).

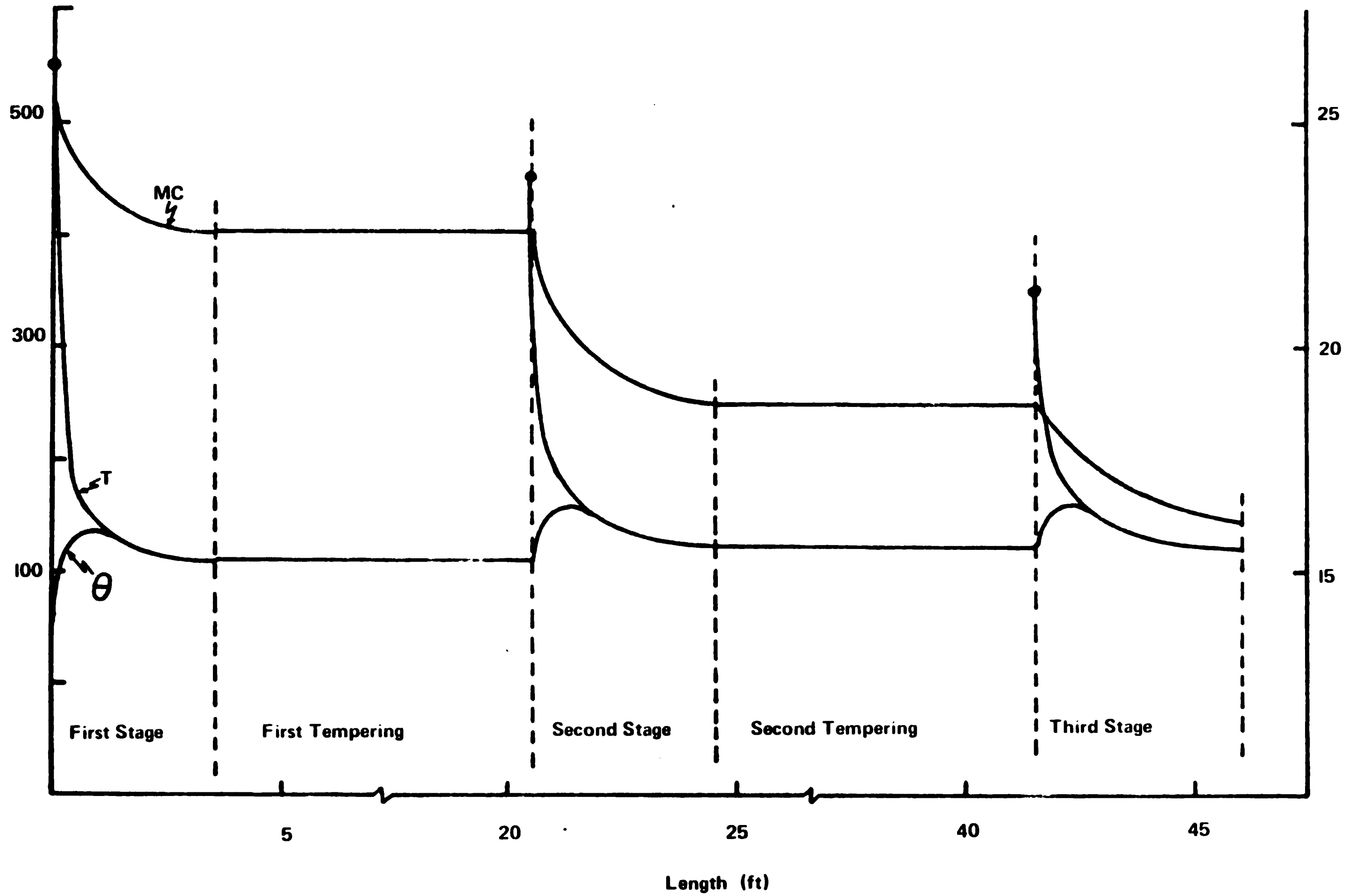


Figure 7.4.5b : Air and kernel temperatures and MC distributions in the CCF (initial MC = 25.5%).

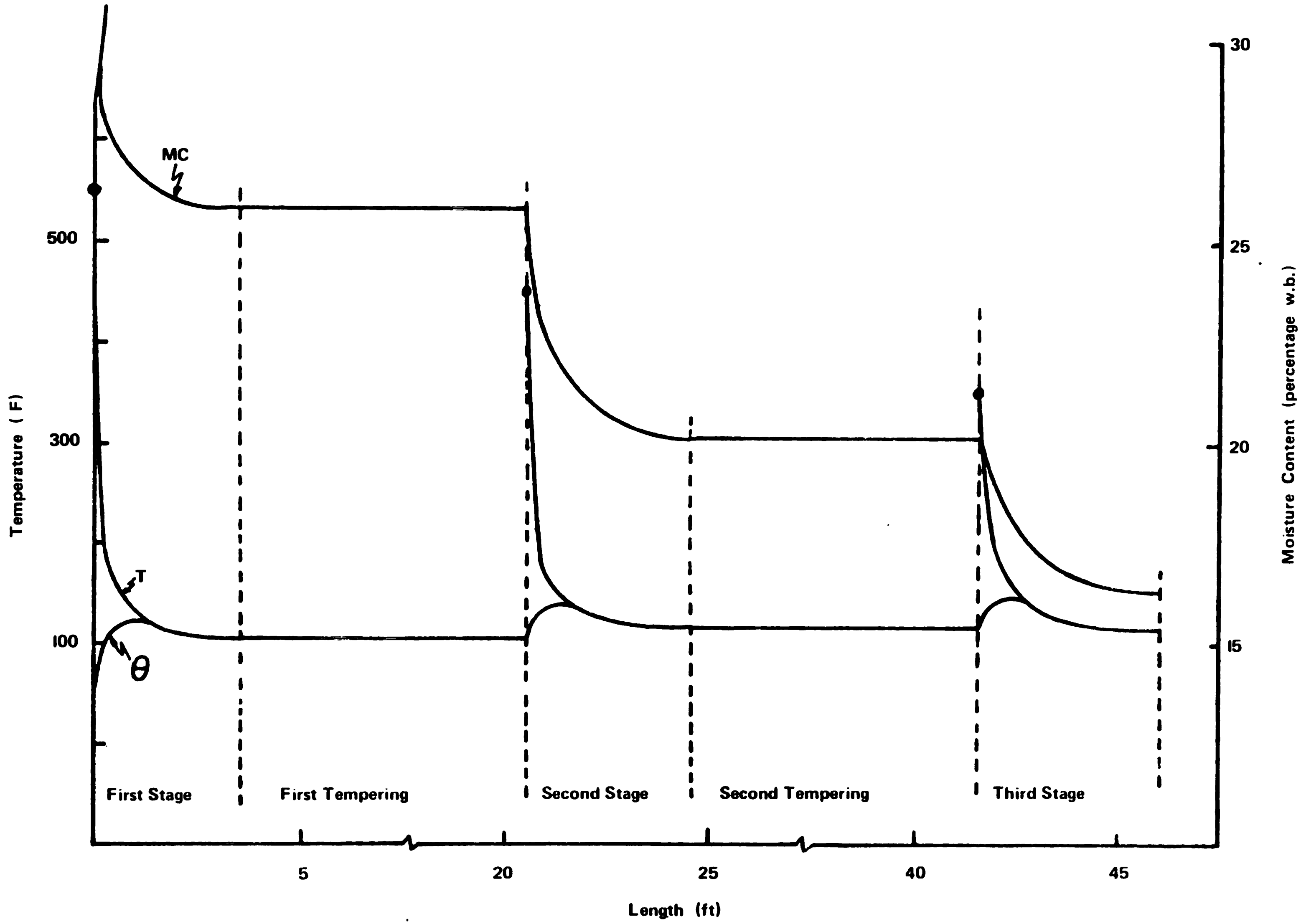


Figure 7.4.5c : Air and kernel temperatures and MC distributions in the CCF (initial MC = 30.0%).

moisture content and the grainflow speed; in general, the combination lower initial moisture content higher grainflow speed leads to a higher grain outlet moisture content;

c. the outlet air from the first stage is more fully saturated than of the second and third drying stages;

d. the exhaust air absolute humidities in the three drying stages are on the order of 0.04-0.08, almost twice as high as in the Blount 10-60;

e. most of the moisture in the three-stage concurrent-flow dryer is removed in the second stage; in the first stage a large percentage of the energy is used for heating up the grain.

7.4.6 Dryer Comparison

In this section the five dryers discussed in the previous five sections are compared directly with respect to the energy efficiency, moisture content gradient and final kernel temperature in removing 5, 10 and 15 points of moisture directly to 15.5 +/- 0.2 percent. Tables 7.4.6-1, 7.4.6-2 and 7.4.6-3 show the data.

Of the four cross-flow dryers the Blount 10-60 is in general the most energy efficient dryer; at 5 points removal this dryer uses only 47% as much energy as the Farm Fans, 57% as much as the Redex, and 66% as much as the Hart-Carter. The 10-60 is even more energy efficient as the present design of the Ferrell-Ross CCF concurrent-flow dryer. Tables 7.4.6-2 and 7.4.6-3 show that at 10 and 15 points removal equally favorable energy efficiencies are obtained by the Blount 10-60 in comparison to the three other cross-flow dryers. The principal reasons for the excellent energy efficiency of the 10-60 appear to be:

a. the recycling of the cooling air;

b. the partial recycling of the drying air;

c. the relatively large thickness of the grain columns (i.e. 14 in. versus 12 in. in the Farm Fans, Redex and Hart-Carter models);

Table 7.4.6-1: Comparison of five dryers operating <u>under standard conditions</u>; initial moisture content 20.5%, final moisture content 15.5 +/- 0.2%, inlet air temperature 200 F (for CCF 550-450-350 F).

Dryer	Max. MC gradient (%)	Average final kernel temp. (F)	Energy efficiency factor (dimensionless)	Predicted[1] energy efficiency (BTU/lb)
FF-AB-8B	3.0	60.9	1.18	3,512
Redex RX-10	3.6	61.2	1.09	2,600
HC-66	1.1	61.0	1.04	2,345
Blount 10-60	0.9	127.7	1.02	1,645
Ferrell-Ross CCF 3-12-12	0.0	68.0	1.00	1,921[2]

[1] Expected dryer efficiency (simulated dryer efficiency times dryer efficiency factor).

[2] Without cooling and air recycling.

D-hybrid =0.95

Table 7.4.6-2: Comparison of five dryers operating under standard conditions; initial moisture content 25.5%, final moisture content 15.5 +/- 0.2%, inlet air temperature 200 F (for CCF 550-450-350 F).

Dryer	Max. MC gradient (%)	Average final kernel temp. (F)	Energy efficiency factor (dimensionless)	Predicted[1] energy efficiency (BTU/lb)
FF-AB-8B	4.9	63.3	1.18	3,004
Redex RX-10	5.6	61.0	1.09	2,309
HC-66	3.0	60.8	1.04	2,138
Blount 10-60	2.5	97.6	1.02	1,464
Ferrell-Ross CCF 3-12-12	0.0	65.0	1.00	1,591[2]

[1] Expected dryer efficiency (simulated dryer efficiency times dryer efficiency factor).

[2] Without cooling and air recycling.

D-hybrid= 0.95

Table 7.4.6-3: Comparison of five dryers operating under standard conditions; initial moisture content 30.5%, final moisture content 15.5 +/- 0.2%, inlet air temperature 200 F (for CCF 550-450-350 F).

Dryer	Max. MC gradient (%)	Average final kernel temp. (F)	Energy efficiency factor (dimensionless)	Predicted[1] energy efficiency (BTU/lb)
FF-AB-8B	6.6	62.6	1.18	2,565
Redex RX-10	7.2	60.9	1.09	2,011
HC-66	4.0	60.7	1.04	1,975
Blount 10-60	3.2	80.7	1.02	1,304
Ferrell-Ross CCF 3-12-12	0.0	61.0	1.00	1,487[2]

[1] Expected dryer efficiency (simulated dryer efficiency times dryer efficiency factor).

[2] Without cooling and air recycling.

D-hybrid= 0.95

d. the relatively low airflow rate (i.e. 90 cfm per bushel versus 100 (or more) cfm per bushel for the Farm Fans, Redex and Hart-Carter models);

e. the tempering of the grain for 0.5 - 1 hour between the first and second drying stages.

At five point moisture removal, the largest moisture content gradient among the cross-flow dryers is found in the Redex dryer and the smallest in the Blount 10-60. For ten and fifteen points removal, the Blount 10-60 and the Hart-Carter dryers have the smallest moisture gradient and the Redex has the largest. The air reversal in the Hart-Carter (between the two drying sections) resulted in a decrease in the moisture gradient, but air reversal between the drying and cooling sections of the Redex did not reduce the moisture gradient. This is due to the lower airflows that the Redex dryer uses. An inherent characteristic of concurrent-flow drying is the absolute uniformity between kernels of the final moisture content; in fact, in properly operating Ferrell-Ross CCF units the moisture gradient is zero, thus even better than for the Blount 10-60.

The average temperature of the corn leaving the dryers is close to the ambient dry bulb temperature except for the Blount 10-60. Increasing the length of the cooling section or increasing the cooling airflow rate will alleviate this problem.

7.5 Design Analysis of Blount 10-60

This section will evaluate the effect of a number of parameters on the performance of the Blount 10-60 with corn with aa D-hybrid=0.95

7.5.1 Effect of Initial Moisture Content

The effect of the initial moisture content on the operation of the Blount 10-60 operating under standard conditions is tabulated in Table 7.5.1. Several points are clear from the simulation results:

a. the dryer efficiency is (as expected) greatly affected by the initial moisture content;

Table 7.5.1: The effect of initial moisture content (and grain flow rate) on the operating conditions of the Blount 10-60 cross-flow dryer at 200 F air inlet and 90 cfm/bu airflow; grains speed ratios 1:2 and 1:1.

	Parameter Values		MC (in)= 20.5% Fan side Gp=28.7 (bu/hr ft^2)	MC (in)= 20.5% Exhaust side Gp=14.4 (bu/hr ft^2)	MC (in)= 25.5% Fan side Gp=15.0 (bu/hr ft2)	MC (in)= 25.5% Exhaust side Gp=7.5 (bu/hr ft^2)	MC (in)= 30.5% Fan side Gp=10.6 (bu/hr ft^2)	MC (in)= 30.5% Exhaust side Gp=5.3 (bu/hr ft^2)	speed ratio 1:1 MC(in)=20.5% Gp=19.2 (bu/hr ft^2)	speed ratio 1:1 MC(in)=25.5% Gp=11.0 (bu/hr ft^2)	speed ratio 1:1 MC(in)=30.5% Gp=7.8 (bu/hr ft^2)
S	MC Gradient (% w.b.)	Min.	15.2	18.9	14.4	20.6	13.8	22.4	13.9	13.3	12.5
		Ave.	17.3	19.4	17.9	21.6	18.6	24.4	17.7	19.3	21.0
T		Max.	19.6	19.8	21.9	22.4	24.6	26.0	20.2	23.6	27.7
A	Temp. gradient (° F)	Min.	160.3	140.1	160.4	140.3	159.3	135.8	137.3	135.5	130.8
G		Ave.	181.1	150.3	182.9	150.7	182.8	148.0	167.9	168.6	167.8
		Max.	193.9	156.6	195.5	157.0	196.2	155.5	195.7	196.7	197.3
E	Hout (decimal)		0.0312		0.0358		0.0386		0.0321	0.0364	0.0397
1	RHout (%)		60.0		60.5		70.0		67.0	67.0	80.0
S	MC gradient (% w.b.)	Min.	15.1	15.5	14.0	16.0	13.3	15.3	14.0	13.2	12.5
		Ave.	15.8	15.9	15.5	16.7	15.6	16.4	15.8	16.1	16.1
T		Max.	16.4	16.4	17.1	17.1	17.1	17.2	17.0	17.8	18.5
A	Temp. gradient (° F)	Min.	168.2	152.3	176.1	158.9	176.6	160.0	151.5	155.6	155.5
G		Ave.	184.5	159.6	188.6	167.1	189.1	168.2	174.1	177.1	178.4
		Max.	194.2	164.0	195.9	172.4	196.7	173.4	195.5	196.7	197.5
L	Hout (decimal)		0.0339		0.0325		0.0334		0.0338	0.0338	0.0357
2	RHout (%)		17.0		18.5		19.0			20.1	22.0
C	MC gradient (% w.b.)	Min.	15.1	15.0	14.0	15.2	13.3	14.6	14.0	13.3	12.4
		Ave.	15.6	15.5	15.3	15.9	15.4	15.6	15.5	15.6	15.5
		Max.	15.9	16.0	16.6	16.6	16.5	16.5	16.4	16.6	16.9
O	Temp. gradient (° F)	Min.	69.3	155.2	60.9	124.7	60.3	93.2	61.6	60.3	60.3
O		Ave.	109.7	163.6	77.3	138.2	67.1	107.8	121.4	96.2	82.8
L		Max.	163.6	168.5	113.5	157.4	85.4	132.0	182.2	160.1	134.4
I	Rout (decimal)		0.0175		0.0147		0.0127		0.0110	0.0102	0.0099
R	RHout (%)		9.5		6.4		6.5		2.5	2.7	3.0
	Time in dryer (and tempering) (min.)		62	95	117	182	165	258	81	142	200
	Grain speed (ft/hr)		35.7	17.8	18.7	9.3	13.2	6.6	23.9	13.7	9.7
	Dryer efficiency (BTU/lb)		1,621		1,435		1,278		1,754	1,482	1,288
	Final Ave. MC (% w.b.)		15.6		15.5		15.4		15.5	15.6	15.5
	Final Ave. Grain (° F)		127.7		97.6		80.7		121.4	96.2	82.8
	Dryer capacity (bu/hr)		528		276		195		471	270	191
	Theor. HP		51		51		51		51	51	51
	Theor. HP/bu cap		0.10		0.18		0.26		0.11	0.18	0.27

b. the maximum moisture gradient at the 2:1 grain velocity ratio is larger for the higher initial moisture contents (i.e. 3.3% and 0.9% for the 30.5% and 20.5% initial moisture contents, respectively);

c. the final grain temperature depends on the grain velocity in the dryer and thus, is lower at the higher initial moisture contents;

d. at three times the moisture removal rate in terms of moisture percentage points (i.e. 15 versus 5 points), the dryer capacity is reduced by 63 percent (or expressing it differently, by increasing the initial moisture content of the grain by a factor of 2.0, the capacity decreases 2.7 fold);

e. at the higher initial moisture contents the grain temperatures during the drying process to 15.5 +/- 0.2% are usually somewhat higher than at lower initial moistures (i.e. there is about a 2-10 degree F difference in grain temperature in the second drying stage between the 20.5

and 30.5 percent runs);

f. the absolute humidity of the exhaust air in the first stage of the Blount 10-60 is higher at higher initial moisture contents, resulting in better energy efficiencies at higher initial moisture contents.

In addition to the data on the Blount 10-60 operating at a certain grain speed ratio, Table 7.5.1 shows results of the Blount 10-60 without the differential grain speed option. The last three columns contain data for the three initial moisture contents of the Blount 10-60 with the grain speed ratio of 1:1. About the Blount 10-60 without the differential grain speed option, the following observations can be made:

a. the higher the initial moisture content, the greater is the overdrying of part of the grain and the larger is the moisture gradient of the dried grain (i.e. 4.5% at MC initial= 30.5% and 2.4% at MC initial= 20.5%;

b. the energy efficiency of the Blount 10-60 with or without differential grain speeds is very good compared to other cross-flow dryers (i.e. at MC initial= 25.5%, about 1450 BTU per pound of water removed).

7.5.2 Effect of Differential Grain Speed Ratio

The effect of the ratio of the grain velocity at the air-inlet side of the grain column to that at the air exhaust side of the column (e.g. the differential grain speed ratio) is illustrated in Table 7.5.2 for the Blount 10-60 operating under standard conditions with a corn inlet moisture content of 25.5 percent; the table includes also data on the Blount 10-60 without the differential grain speed option (1:1 ratio).

The salient points in Table 7.5.2 are:

a. the optimum differential grain speed ratio (i.e. when the average moisture content difference between the grain at the air inlet and air exhaust side is at a minimum at the dryer outlet) is a function of the inlet moisture content;

b. differential grain velocities in the grain

Table 7.5.2: Effect of the differential speed ratio (and grain flow rate) on the operating conditions of the Blount 10-60 cross-flow dryer at 200° F air inlet, 90 cfm/bu airflow and 25.5% initial moisture content.

Stage	Parameter Values		2:1 ratio Fan side GP= 15.0 (bu/hr ft^2)	2:1 ratio Exhaust side Gp= 7.5 (bu/hr ft^2)	3:1 ratio Fan side Gp= 17.0 (bu/hr ft^2)	3:1 ratio Exhaust side Gp= 5.6 (bu/hr ft^2)	4:1 ratio Fan side Gp= 18.3 (bu/hr ft^2)	4:1 ratio Exhaust side Gp= 4.6 (bu/hr ft^2)	1:1 ratio One speed with tempering and mixing Gp= 11.0 (bu/hr ft^2)	1:1 ratio One speed with tempering no mixing Gp= 10.9 (bu/hr ft^2)	1:1 ratio One speed no tempering no mixing Gp= 10.9 (bu/hr ft^2)
STAGE 1	MC gradient (% w.b.)	Min.	14.4	20.6	14.9	20.0	15.2	19.4	13.3	13.3	13.3
		Ave.	17.9	21.6	18.6	21.2	19.0	20.8	19.3	19.2	19.2
		Max.	21.9	22.4	22.7	22.7	22.9	22.9	23.6	23.4	23.4
	Temp. gradient (° F)	Min.	160.4	140.3	156.9	140.6	154.5	141.7	135.5	135.9	135.9
		Ave.	182.9	150.7	180.3	148.7	178.7	148.2	168.6	168.9	168.9
		Max.	195.5	157.0	194.8	153.6	194.3	152.1	196.7	196.8	196.8
	Hout (decimal)		0.0358		0.0356		0.0356		0.0364	0.0364	0.0364
	RHout (%)		60.5		59.0		59.0		67.0	67.0	67.0
STAGE 2	MC gradient (% w.b.)	Min.	14.0	16.0	14.2	15.6	14.4	15.1	13.2	13.2	11.5
		Ave.	15.5	16.7	15.7	16.5	16.1	16.1	16.1	16.0	15.9
		Max.	17.1	17.1	17.5	17.5	17.7	17.7	17.8	17.7	18.3
	Temp. gradient (° F)	Min.	176.1	158.9	173.5	158.5	172.2	158.9	155.6	155.9	157.6
		Ave.	188.6	167.1	187.5	165.6	186.7	165.2	177.1	177.4	178.5
		Max.	195.9	172.4	195.5	170.3	195.3	169.4	196.7	196.7	197.9
	Hout (decimal)		0.0325		0.0342		0.0338		0.0338	0.0338	0.0337
	RHout (%)		18.5		20.5		20.5		20.1	20.1	18.5
COOLER	MC gradient (% w.b.)	Min.	14.0	15.2	14.3	14.6	14.4	13.8	13.3	13.2	11.6
		Ave.	15.3	15.9	15.5	15.5	15.8	15.1	15.6	15.5	15.3
		Max.	16.6	16.6	16.9	16.9	16.9	16.9	16.6	16.5	17.0
	Temp. gradient (° F)	Min.	60.9	124.7	61.5	135.5	61.8	147.8	60.3	60.3	60.4
		Ave.	77.3	138.2	83.6	144.6	88.1	154.3	96.2	96.3	103.8
		Max.	113.5	157.4	127.9	158.1	140.0	164.1	160.1	160.3	168.9
	Hout (decimal)		0.0147		0.0155		0.0137		0.0102	0.0101	0.0094
	RHout (%)		6.4		7.5		6.2		2.7	2.6	2.1
	Time in dryer (tempering zone) (min.)		117	182	109	226	104	265	142	91 (0)	91 (0)
	Grain speed (ft/hr)		18.7	9.3	21.1	6.9	22.8	5.7	13.7	13.6	13.6
	Dryer efficiency (BTU/1b)		1,435		1,445		1,455		1,482	1,486	1,461
	Final Ave. MC (% w.b.)		15.5		15.5		15.7		15.6	15.5	15.3
	Final Ave. Grain temp. (° F)		97.6		98.7		101.4		96.2	96.3	103.8
	Dryer capacity (bu/hr)		276		278		280		270	267	267

column result in less overdrying of the grain at the air inlet side (i.e. the 1:1 ratio dryer overdries the corn to 13.3%, the 3:1 only to 14.3%);

c. the grain velocity ratio has little effect on the energy efficiency of the dryer;

d. the mixing of the grain in the Blount 10-60 between the first and second drying stages has a larger effect on the moisture gradient of the dryer outlet grain sample than differential grain speeds in the columns (note the last column in Table 7.5.1 in which the minimum moisture content after non-mixing at a 1:1 speed ratio is 11.6 percent versus 13.3% after mixing);

e. the maximum grain temperature is not influenced much by the grain speed ratio; however, the length of time the same grain is at the maximum temperature is much less in the case of the differential speed models;

f. the average absolute humidity values of the exhaust air in the two drying sections is practically independant of the grain speed ratio;

g. the 10-60 dryer capacity is slightly (5%) higher for a differential speed model than an equivalent conventional unit.

7.5.3 Effect of Column Thickness

The effect of the column thickness on the operation of the Blount 10-60 at an initial moisture content of 25.5 percent operating under standard conditions is illustrated in Table 7.5.3. The main conclusions to be drawn from the simulations are:

a. an increase in the column thickness improves in general the energy efficiency (an exception is the 14" column for an unexplained reason);

b. the maximum moisture content gradient in the grain column is not affected by the column width (a very surprising result);

Table 7.5.3: Effect of the column thickness (and grain flow rate) on the operating conditions of the Blount 10-60 cross-flow dryer at 200 F air inlet, 90cfm/bu airflow, and 25.5% initial moisture content.

Parameter Values		12 in. column Fan side Gp= 14.0 (bu/hr ft^2)	12 in. column Exhaust side Gp= 7.0 (bu/hr ft^2)	14 in. column Fan side Gp= 15.0 (bu/hr ft^2)	14 in. column Exhaust side Gp= 7.5 (bu/hr ft^2)	16 in. column Fan side Gp= 14.8 (bu/hr ft^2)	16 in. column Exhaust side Gp= 7.4 (bu/hr ft^2)	18 in. column Fan side Gp= 14.5 (bu/hr ft^2)	18 in. column Exhaust side Gp= 7.3 (bu/hr ft^2)	18 in. column- One speed Gp=10.2 (bu/hr ft^2)
STAGE 1 MC gradient (% w.b.)	Min.	14.2	20.7	14.4	20.6	14.4	20.7	14.3	20.7	13.0
	Ave.	18.0	21.9	17.9	21.6	18.0	21.8	18.1	21.9	19.2
	Max.	22.2	22.9	21.9	22.4	22.2	22.7	22.3	22.9	23.7
Temp. gradient (° F)	Min.	157.1	134.5	160.4	140.3	159.5	137.3	157.7	136.2	134.3
	Ave.	180.6	145.7	182.9	150.7	182.2	148.3	181.7	146.9	168.7
	Max.	194.9	152.5	195.5	157.0	196.2	155.7	196.8	154.5	197.7
Hout (decimal)		0.0365		0.0358		0.0361		0.0363		0.0371
RHout (%)		69.0		60.5		62.0		68.0		68.0
STAGE 2 MC gradient (% w.b.)	Min.	13.9	16.4	14.0	16.0	14.0	15.8	14.0	15.9	12.9
	Ave.	15.6	17.0	15.5	16.7	15.6	16.7	15.7	16.7	15.9
	Max.	17.3	17.3	17.1	17.1	17.3	17.3	17.4	17.4	17.6
Temp. gradient (° F)	Min.	171.3	154.5	176.1	158.9	173.7	157.3	172.7	156.3	154.6
	Ave.	186.4	162.0	188.6	167.1	187.6	164.8	187.2	163.7	176.9
	Max.	195.3	166.9	195.9	172.4	196.4	170.6	196.9	170.0	197.6
Hout (decimal)		0.0334		0.0325		0.0344		0.0335		0.0345
RHout (%)		20.0		18.5		19.0		19.5		21.0
COOLER MC gradient (% w.b.)	Min.	13.9	15.5	14.0	15.2	14.1	15.0	14.0	15.0	13.0
	Ave.	15.4	16.1	15.3	15.9	15.4	15.9	15.5	15.9	15.5
	Max.	16.7	16.7	16.6	16.6	16.7	16.7	16.7	16.7	16.4
Temp.gradient (° F)	Min.	60.9	128.6	60.9	124.7	60.5	128.0	60.3	131.3	60.2
	Ave.	78.6	140.7	77.3	138.2	77.5	143.5	77.8	147.8	96.2
	Max.	117.2	156.9	113.5	157.4	116.8	161.4	120.7	163.9	160.3
Hout (decimal)		0.0155		0.0147		0.0161		0.0164		0.0109
RHout (%)		7.0		6.4		7.5		7.8		2.8
Time in dryer (and tempering) (min.)		(55) 125	(55) 195	(52) 117	(52) 182	(52) 118	(52) 184	121 (53)	188 (53)	(57) 154
Grain speed (ft/hr)		17.4	8.7	18.7	9.3	18.4	9.2	18.0	9.0	12.7
Dryer efficiency (BTU/1b)		1,603		1,435		1,465		1,523		1,561
Final Ave. MC (% w.b.)		15.7		15.5		15.6		15.6		15.5
Final Ave. Grain temp. (° F)		99.3		97.6		99.5		101.2		96.2
Dryer capacity (bu/hr)		222		276		313		345		323
Theor. HP		33.5		51.0		73.7		102.3		102.2
Theor. HP/bu cap		0.15		0.18		0.24		0.30		0.32

c. the capacity of the Blount 10-60 is a direct function of the column thickness; of course, this larger capacity requires an equivalent increase in fan horsepower;

d. column thickness has little effect on the grain temperatures and exhaust absolute humidities in a Blount 10-60 type dryer.

7.5.4 Effect of Airflow Rate

The effect of the rate of airflow on the output characteristics of the Blount 10-60 operating under standard conditions is illustrated in Table 7.5.4. Several observations can be made about the simulated data:

a. the energy efficiency decreases slightly at increased airflows between 70 and 110 cfm/bu for an initial grain moisture content of 25.5 percent;

b. a twenty two percent increase in airflow rate results in a twenty percent increase

Table 7.5.4: Effect of the airflow rate (and grain flow rate) on the operating conditions of the Blount 10-60 cross-flow dryer at 200 °F air inlet and 25.5% initial moisture content; grain speed ratio 1:2.

	Parameter Values		70 cfm/bu Fan side Gp= 12.8 (bu/hr ft^2)	70 cfm/bu Exhaust side Gp= 6.4 (bu/hr ft^2)	90 cfm/bu Fan side Gp= 15.0 (bu/hr ft^2)	90 cfm/bu Exhaust side Gp= 7.5 (bu/hr ft^2)	110 cfm/bu Fan side Gp= 18.0 (bu/hr ft^2)	110 cfm/bu Exhaust side Gp= 9.0 (bu/hr ft^2)
STAGE 1	MC gradient (% w.b.)	Min.	13.9	20.7	14.4	20.6	15.0	20.9
		Ave.	17.8	21.8	17.9	21.6	18.3	21.8
		Max.	22.0	22.9	21.9	22.4	22.0	22.5
	Temp. gradient (° F)	Min.	155.8	132.8	160.4	140.3	161.0	143.4
		Ave.	179.9	144.4	182.9	150.7	183.7	152.2
		Max.	194.8	151.3	195.5	157.0	195.6	157.5
	Hout (decimal)		0.0370		0.0358		0.0351	
	RHout (%)		70.0		60.5		56.0	
STAGE 2	MC gradient (% w.b.)	Min.	13.6	15.7	14.0	16.0	14.7	15.8
		Ave.	15.6	16.5	15.5	16.7	15.6	16.5
		Max.	17.1	17.1	17.1	17.1	17.2	17.2
	Temp. gradient (° F)	Min.	170.7	154.2	176.1	158.9	177.1	160.6
		Ave.	185.9	161.7	188.6	167.1	189.1	168.9
		Max.	195.2	165.5	195.9	172.4	196.0	174.0
	Hout (decimal)		0.0341		0.0325		0.0332	
	RHout (%)		20.0		18.5		18.0	
COOLER	MC gradient (% w.b.)	Min.	13.6	14.9	14.0	15.2	14.7	15.2
		Ave.	15.4	15.8	15.3	15.9	15.5	15.9
		Max.	16.4	16.4	16.6	16.6	16.7	16.7
	Temp. gradient (° F)	Min.	60.9	134.3	60.9	124.7	61.1	129.2
		Ave.	80.9	143.9	77.3	138.2	79.8	141.3
		Max.	122.5	156.2	113.5	157.4	118.5	158.2
	Hout (decimal)		0.0154		0.0147		0.0149	
	RHout (%)		8.0		6.4		6.8	
Time in dryer (and tempering) (min.)			136 (60)	213 (60)	117 (52)	182 (52)	93 (43)	143 (43)
Grain speed (ft/hr)			15.9	8.0	18.7	9.3	22.4	11.2
Dryer efficiency (BTU/lb)			1,348		1,435		1,476	
Final Ave. MC (% w.b.)			15.5		15.5		15.6	
Final Ave. temp. (° F)			101.9		97.6		100.3	
Dryer capacity (bu/hr)			235		276		331	
Theor.HP			26		51		89	
Theor.HP/bu cap			0.11		0.18		0.27	

in capacity; a twenty two percent decrease in airflow results in a 15 percent decrease in capacity;

c. at higher airflow rates the moisture gradient in the dried grain is slightly lower than at low airflows (i.e. 2.0% at 110 cfm/bu versus 2.8% at 70 cfm/bu);

d. the maximum grain temperatures are not affected by the airflow rate;

e. at higher airflow rates the grain is maintained at the maximum temperature for a shorter period of time;

f. the average final grain temperature is not affected by the airflow rate within the 70-110 cfm/bu range.

7.5.5 Effect of Drying Temperature

The effect of the inlet air temperature on the operation of the Blount 10-60 is illustrated in Table 7.5.5. The main conclusions to be drawn

Table 7.5.5: Effect of the drying air temperature (and grain flow rate) on the operating conditions of the Blount 10-60 cross-flow dryer at 90 cfm/bu and 25.5% initial moisture content; grain speed ratio 1:2.

	Parameter Values		175 °F inlet air temp.		200 °F inlet air temp.		225 °F inlet air temp.	
			Fan side Gp= 9.9 (bu/hr ft^2)	Exhaust side Gp= 5.0 (bu/hr ft^2)	Fan side Gp= 15.0 (bu/hr ft^2)	Exhaust side Gp= 7.5 (bu/hr ft^2)	Fan side Gp= 21.3 (bu/hr ft^2)	Exhaust side Gp= 10.7 (bu/hr ft^2)
STAGE 1	MC gradient (% w.b.)	Min.	14.5	19.0	14.4	20.6	14.2	22.1
		Ave.	18.0	19.9	17.9	21.6	18.3	23.1
		Max.	20.8	20.8	21.9	22.4	22.8	24.2
	Temp. gradient (°F)	Min.	153.2	140.9	160.4	140.3	160.7	134.4
		Ave.	164.3	147.1	182.9	150.7	198.0	148.0
		Max.	171.9	150.8	195.5	157.0	218.3	156.2
	Hout (decimal)		0.0305		0.0358		0.0439	
	RHout (%)		48.0		60.5		78.0	
STAGE 2	MC gradient (% w.b.)	Min.	14.2	15.8	14.0	16.0	14.3	15.1
		Ave.	15.4	16.2	15.5	16.7	15.6	15.9
		Max.	17.1	17.1	17.1	17.1	16.8	16.8
	Temp. gradient (°F)	Min.	160.0	152.7	176.1	158.9	185.3	161.3
		Ave.	167.8	156.4	188.6	167.1	206.1	173.1
		Max.	172.3	158.6	195.9	172.4	218.4	180.4
	Hout (decimal)		0.0273		0.0325		0.0440	
	RHout (%)		17.0		18.5		23.0	
COOLER	MC gradient (% w.b.)	Min.	14.2	15.2	14.0	15.2	14.3	14.4
		Ave.	15.3	16.0	15.3	15.9	15.3	15.3
		Max.	16.7	16.7	16.6	16.6	16.1	16.1
	Temp. gradient (°F)	Min.	60.3	81.5	60.9	124.7	64.2	169.8
		Ave.	64.6	92.2	77.3	138.2	100.3	171.8
		Max.	76.3	110.8	113.5	157.4	159.1	178.3
	Hout (decimal)		0.0111		0.0147		0.0196	
	RHout (%)		8.0		6.4		8.4	
Time in dryer (and tempering) (min.)			178 (78)	276 (78)	117 (52)	182 (52)	82 (36)	128 (36)
Grain speed (ft/hr)			12.3	6.2	18.7	9.3	26.5	13.2
Dryer efficiency (BTU/lb)			1,677		1,435		1,259	
Final Ave. MC (% w.b.)			15.5		15.5		15.3	
Final Ave. Temp. (°F)			73.8		97.6		124.1	
Dryer capacity (bu/hr)			182		276		392	

from the simulations are:

a. an increase of 50 F in the inlet air temperature increases the capacity by 115 percent (i.e. from 182 to 392 bu/hr);

b. an increase of 50 F in the inlet air decreases the energy consummption by 25 percent (i.e. from 1677 to 1259 BTU/lb);

c. the present cooler design of the Blount 10-60 is sufficient for an inlet air temperature of 175 F, but is underdesigned for higher inlet air temperatures;

d. the maximum moisture content gradient occurs at the lowest air temperature (i.e. 2.5% at 175 F versus 1.8% at 225 F);

e. the maximum grain temperatures are within 8 F of the inlet air temperature.

7.5.6 Modified Design

The effect of a change in dryer and cooler column lengths in the basic Blount 10-60 design is tabulated in Table 7.5.6. The original dryer (cooler column lengths of 12'-6.7'-1.6' were changed to 18'-7'-4' with tempering between the first two drying stages (as in the basic design). The results of these changes are:

a. the energy efficiency is not affected;

b. the dryer capacity increases 40 percent (i.e. increases from 276 to 386 bu/hr for 10 points moisture removal);

c. the average kernel temperature is almost 30 F lower;

d. the moisture gradient of the dried grain is slightly less;

e. the longer dryer/cooler model results in slightly lower grain temperatures and longer residence times during the drying process.

Table 2.5.6: Effect of the column length and location of tempering on the operating conditions of the Blount 10-60 cross-flow dryer at 200 °F and 225 °F air inlet, 90 cfm/bu and 25.5% initial moisture content.

	Parameter	Values	12 - T - 6.7 - 1.6 (1) Fan side 200°F Gp= 15.0 (bu/hr ft^2)	12 - T - 6.7 - 1.6 (1) Exhaust side Gp= 7.5 (bu/hr ft^2)	18 - T - 7 - 4 (2) Fan side 200°F Gp= 21.0 (bu/hr ft^2)	18 - T - 7 - 4 (2) Exhaust side Gp= 10.5 (bu/hr ft^2)	18 - T - 7 - 4 Fan side 225°F Gp= 30.0 (bu/hr ft^2)	18 - T - 7 - 4 Exhaust side Gp= 15.0 (bu/hr ft^2)
STAGE 1	MC gradient (% w.b.)	Min.	14.4	20.6	14.2	20.1	14.0	21.7
		Ave.	17.9	21.6	17.4	21.1	17.8	22.6
		Max.	21.9	22.4	21.1	21.9	22.1	23.7
	Temp. gradient (°F)	Min.	160.4	140.3	161.2	143.2	142.4	164.5
		Ave.	182.9	150.7	184.0	152.2	180.9	200.2
		Max.	195.5	157.0	195.8	157.5	210.7	218.8
	Hout (decimal)		0.0358		0.0338		0.0393	
	RHout (%)		60.5		57.0		70.0	
STAGE 2	MC gradient (% w.b.)	Min.	14.0	16.0	14.3	16.0	14.7	16.2
		Ave.	15.5	16.7	15.6	16.6	15.9	16.5
		Max.	17.1	17.1	17.3	17.3	16.9	16.9
	Temp. gradient (°F)	Min.	176.1	158.9	172.7	156.8	179.0	154.3
		Ave.	188.6	167.1	186.9	164.0	203.0	165.2
		Max.	195.9	172.4	195.3	168.9	217.2	172.6
	Hout (decimal		0.0325		0.0312		0.0393	
	RHout (%)		18.5		17.5		23.0	
COOLER	MC gradient (% w.b.)	Min.	14.0	15.2	14.4	15.2	14.8	15.1
		Ave.	15.3	15.9	15.4	15.8	15.6	15.4
		Max.	16.6	16.6	16.7	16.7	16.1	16.1
	Temp. gradient (°F)	Min.	60.9	124.7	60.2	73.7	60.5	111.1
		Ave.	77.3	138.2	62.8	82.2	72.9	124.9
		Max.	113.5	157.4	70.0	97.4	101.5	146.1
	Hout (decimal)		0.0147		0.0118		0.0146	
	RHout (%)		6.4		8.1		6.2	
Time in dryer (and tempering) (min.)			117 (52)	182 (52)	122 (55)	189 (55)	85 (38)	133 (38)
Grain speed (ft/hr)			18.7	9.3	26.1	13.1	37.3	18.7
Dryer efficiency (BTU/lb)			1,435		1,426		1,232	
Final Ave. MC (% w.b.)			15.5		15.5		15.5	
Final Ave. Temp. (°F)			97.6		69.3		90.2	
Dryer capacity (bu/hr)			276		386		552	
Theor. HP			51.0		72.9		72.9	
Theor. HP/bu cap			0.18		0.19		0.13	

(1): The dryer as tested: 12' first stage, tempering, 6.7' second stage, and 1.6' cooler.

(2): Proposed design one: 18' first stage, tempering, 7' second stage, and 4' cooler.

7.5.7 Conclusions

In the previous part of this section (7.5) the different parameters which influence the operation of the Blount 10-60, the most advanced cross-flow grain dryer on the market, were analysed. The main conclusions from this part of the simulation study are:

a. the effect of grain mixing between the first and second drying stages (in order to minimize the moisture gradient in the dried grain) is more pronounced than the effect of differential grain speeds in the grain columns;

b. the differential grain speed ratio contributes (along with the mixing of the grain before tempering) to the minimizing of the moisture gradients across the grain columns; the optimum value of the grain speed ratio is dependent upon the initial moisture content of the grain;

c. the differential grain speed option does not significantly improve the energy efficiency of the dryer;

d. the tempering in the dryer does not significantly increase the drying capacity but appears to contribute to an improvement of the grain quality;

e. the 14" column thickness in the present design can be increased to 16-18" in order to increase the dryer capacity without materially affecting the size of the moisture gradient in the dried grain (of course, the fan horsepower needs to be increased accordingly);

f. increasing the airflow rate per bushel by about 20 percent is an wexcellent alternative for increasing the capacity by about the same value;

g. the capacity of the dryer should be rated at 210-225 F rather than at 190-200 F since the capacity is 42 percent higher at the higher drying air temperature;

h. the cooler length of the present Blount 10-60 design should be increased to 4-5 ft in order to ensure adequate cooling when low initial moisture content grain is dried at high inlet air temperatures.

CHAPTER 8

SUMMARY AND CONCLUSIONS

This grain drying investigation has been concerned with the evaluation of the state-of-the art on-farm and off-farm drying of shelled corn in the Midwestern United States in the early nineteen eighties. Although it was impossible to study all available dryer systems, the most prevalent dryers were included in this investigation. The two major criteria used in the evaluation were: (1) energy efficiency, and (2) grain breakage susceptibility increase. The energy efficiencies were obtained by measuring or calculating fossil fuel usage in the drying process; the grain quality was either measured in terms of increase in grain breakage (or by calculating the moisture gradient in the dried grain).

Five drying systems were analyzed. Experimental data on these dryers was obtained at farms and grain elevators in Michigan, Ohio, Kentucky and Ontario (Canada). The data was collected over a period of three drying seasons (1979-1981). A total of well over one million bushels of corn was dried during this period.

The five drying systems included: (1) an on-farm automatic batch dryer, (2) an on-farm continuous flow cross-flow dryer with recycling of the cooling air, (3) an elevator type continuous flow cross-flow dryer with drying/cooling air recirculation, (4) an on-farm/off-farm continuous flow cross-flow dryer with drying/cooling air recirculation, grain tempering and differential grain speeds, and (5) an elevator type three-stage concurrent-flow dryer. Each of the five dryers is commercially available.

Proper engineering evaluation of the dryers required in addition to experimental data, an acceptable simulation model of each of the units. Modification of the existing MSU drying models constituted a major part of the study.

The experimental and simulation data furnished the necessary information for the in-depth analysis of the five dryers investigated in this thesis. The major conclusions of the investigation are:

a. Recycling of exhaust air in cross-flow dryers can improve the energy efficiency by 40-60 percent but also decreases the dryer capacity by 10-15 percent.

b. Reversal of the airflow direction in a cross-flow dryer decreases the moisture gradient from 4-10 percent to 2-4 percent, and the overdrying of part of the grain from 11-12% MC to 13-14% MC.

c. Drying the grain in two drying stages separated by a mixing/tempering stage decreases the moisture gradient of the dried grain in a cross-flow dryer from 4-10 percent to 1-3 percent.

d. The principle of differential grain speeds in the columns of a cross-flow dryer contributes significantly to a lessening of the problem of overdrying of part of the grain.

e. A differential grain speed dryer can be designed with wider grain columns (up to 18 in.) than a conventional cross-flow dryer.

f. Products dried in a differential grain speed dryer maintain a high temperature for a shorter period of time than in conventional cross-flow dryers.

g. The optimum grain speed ratio in a differential grain speed dryer depends on the initial product moisture content, the drying air temperature and the type of product.

h. The tempering of the grain in a differential speed cross-flow dryer contributes more to the improvement of grain quality than to the increase of dryer capacity.

i. The differential grain speed cross-flow dryer is the most technically advanced and potentially most successful cross-flow grain dryer as yet introduced commercially.

j. The multi-stage concurrent-flow dryer out performs any cross-flow dryer with respect to energy efficiency and grain quality.

CHAPTER 9

SUGGESTIONS FOR FUTURE STUDY

Since this study was initiated a new commercial dryer has been introduced in the USA, the microwave dryer. The results of the four cross-flow dryers and one concurrent-flow dryer in this study should be compared to those obtained under standard conditions with the microwave dryer.

In addition, a number of points need to be clarified about the five dryers investigated in this study. These include:

a. How can a redesign of the internal auger system of the Blount 10-60 improve the grain quality characteristics of the dryer?

b. Is the differential grain speed feature of the Blount 10-60 justified for low value crops such as corn or should it only be implemented for such crops as rice and almonds?

c. What type of control and internal product handling should be implemented on a differential speed cross-flow dryer to maximize its effectiveness and grain quality characteristics?

d. Can the energy efficiency, dryer capacity and grain quality characteristics of the multi-stage concurrent-flow dryers be significantly improved by modifying (decreasing) the bed - depths and airflows?

e. Is it necessary to develop non-steady state drying models for microprocessor control of cross-flow and concurrent-flow dryers?

CHAPTER 10

RELEVANCY OF RESULTS TO ARGENTINA

As mentioned in Chapter 3, 70 percent of the corn produced in Argentina has to be artificially dried. From the results obtained in this thesis the following recommendations are proposed in order to improve the drying systems in Argentina:

a. For small on-farm operations, a dryer similar to the Redex RX-10 (i.e. continuous cross-flow with cooling air recirculation type dryer) appears to be an excellent choice. This dryer type can save farmers about 20-30 percent of the fuel when compared to batch drying (the most commonly used at present in small farming operations in Argentina).

b. For medium to large on-farm operations, the Blount 10-60 type dryer appears to be the preferred choice. This dryer not only saves fuel (around 46 percent), but will also yield better quality corn than the conventional continuous cross-flow dryers at present in use at these farms in Argentina.

c. For the large grain elevators the Ferrell-Ross multistage CCF concurrent-flow dryer is the best choice. This type of dryer is potentially the most efficient commercial dryer on the market today and the corn quality is not only maintained but in some cases improved.

REFERENCES

Aguilar, C.S., and D.S. Boyce. 1966. Temperature ratios for measuring efficiency and for the control of driers. J. Agr. Engng. Res. 11 (1): 19-23.

Ahmadnia, A. 1977. The quality of soft wheat dried in a concurrent-countercurrent dryer. Unpublished M.S. thesis, Michigan State University:East Lansing, MI.

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

Bakker-Arkema, F.W. 1980. Performance evaluation of batch and continuous flow dryers. Preliminary report No. 2. Presented at the 1980 Fall Meeting FIEI-Crop Dryer Manufacturers Council: Baton Rouge, LA.

Bakker-Arkema, F.W. 1982. Personal communication.

Bakker-Arkema, F.W., R.C. Brook, and L.E. Lerew. 1978. Cereal Grain Drying. In: Advances in Cereal Science and Technology, Vol. II, Y. Pomeranz, Ed. Am. Assn. Cer. Chem. , Inc.: St. Paul, MN.

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

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

Bakker-Arkema, F.W., S. Fosdick, and J.L. Naylor. 1979. Testing of commercial cross-flow grain dryers. ASAE Paper No. 79-3521. Am. Soc. Agr. Engr.: St. Joseph, MI.

Bakker-Arkema, F.W., L.E. Lerew, R.C. Brook, and D.B.

Brooker. 1978b. Energy and capacity performance evaluation of grain dryers. ASAE Paper No. 78-3523.Am.Soc.Agr.Engr.: St. Joseph, MI.

Bakker-Arkema, F.W., L.E. Lerew, S.F. DeBoer, and M. G. Roth. 1974. Grain dryer simulation. Michigan State University, Agr. Exp. Sta., Res. Bull.No. 224.

Bakker-Arkema, F.W., and J.C. Rodriguez. 1982. Research report on the Blount/MFS 10-60 Continuous-Flow Recirculating Dryer. MSU-Blount, Inc. Cooperative Research Project. Michigan State University: East Lansing, MI.

Bakker-Arkema, F.W., A.A. Sokhansaj, and R. Green. 1977. High temperature wheat drying. ASAE Paper No. 77-3527. Am. Soc. Agr. Engr.: St. Joseph, MI.

Bauer, W.W., L.P. Walker, and F.W. Bakker-Arkema. 1977. Testing of a commercial sized conventional cross-flow and modified cross-flow grain dryer. ASAE Paper No. 77-3014. Am. Soc. Agr. Engr.: St. Joseph, MI.

Brook, R.C. 1977. Design of multistage grain dryers. Unpublished Ph.D. thesis, Michigan State University: East Lansing, MI.

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

Chowdhury, M.R., and G.L. Kline. 1978. Stress cracks in corn kernels from compression loading. ASAE Paper No. 78-3541.Am.Soc. Agr.Engr.: St. Joseph, MI.

Chu, S.T. and A. Hustrulid. 1968. Numerical solution of the diffusion equation. Trans. ASAE 11 (5): 705-710,715.

Converse, J.O. 1972. A commercial cross-flow grain dryer: The Hart-Carter dryer. ASAE Paper No. 72-828. Am. Soc. Agr. Engr.: St. Joseph, MI.

Crank, J. 1976. The Mathematics of Diffusion. Oxford University Press, Oxford, Great Britain.

Dalpasquale, V.A. 1981. Drying soybeans in continuous-flow dryers and fixed-bed drying systems. Unpublished Ph.D. thesis, Michigan State University: East Lansing, MI.

de Dios, C.A., and R.C. Puig. 1981. Comparacion de dos sistemas de secado de maiz. EERA Pergamino, Buenos Aires, Argentina.

Emam, A., M.R. Okos, G.H. Foster, and M. Fortes. 1979. Effect of tempering time on quality of dried corn. ASAE Paper No. 79-3532.Am.Soc.Agr.Engr.: St. Joseph, MI.

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

Fernandez, V., and A.M. Acuna. 1979. Comercializacion de cereales y oleaginosas. FCA Balcarce, Universidad Nacional de Mar del Plata, Balcarce, Buenos Aires, Argentina.

Fortes, M., and M.R. Okos. 1979. Changes in physical properties of corn during drying. ASAE Paper No. 79-3054.Am.Soc.Agr. Engr.: St. Joseph, MI.

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

Gustafson, R.J., and R.V. Morey. 1981. Moisture and quality variations across the column of a cross-flow grain dryer. Trans. ASAE 24 (6): 1621-1615.

Gustafson, R.J., and R.V. Morey. 1979. Study of factors affecting quality changes during high temperature drying. Trans. ASAE 22 (4): 926-932.

Gustafson, R.J., R.V. Morey, C.M. Christensen, and R.A. Meronouch. 1978. Quality changes during high-low temperature drying. Trans. ASAE 21 (1): 162-169.

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

Hall, G.E. 1974. Damage during handling of shelled corn and soybeans. Trans. ASAE 17 (2): 335-338.

Hall, G.E., and L.D. Hill. 1973. Test weight as a grading factor for shelled corn. AERR No. 124. Department of Agricultural Economics: University of Illinois, Urbana, IL.

Hawk, A.L., R.T. Noyes, C.M. Westelaken, G.H. Foster, and F.W. Bakker-Arkema. 1978. The present status of commercial grain grying. ASAE Paper No. 78-3008. Am. Soc. Agr. Engr.: St. Joseph , MI.

Hill, L.D., and A.H. Jensen. 1976. The role of grades and standards in identifying nutritive value of grains. Presented at the fifth annual meeting of the Anderson Research Fund: Ohio State University, Columbus, OH.

Holtman, J.B., and G.L. Zachariah. 1969. Continuous flow modeling for optimal control. Trans. ASAE 12(4):430-432,442.

Katic, Z. 1973. Maiskornbeschadigung bei kunstlicher Trocknung. Muhle and Mischfuttertechnik 110: 534-539.

Lerew, L.E., F.W. Bakker-Arkema, and R.C. Brook. 1972. Simulation of a commercial cross-flow dryer: The Hart-Carter model. ASAE Paper No. 72-829. Am.Soc.Agr. Engr.: St. Joseph, MI.

Maddex, R.L., and F.W. Bakker-Arkema. 1978. Reducing energy requirements for harvesting, drying and storing grain. Extension Bulletin E-1168, Michigan State University: East Lansing, MI.

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

Miller, B.S., J.W. Hughes, R. Rousser, and Y. Pomeranz. 1979. Standard method for measuring breakage susceptibility of shelled corn. ASAE Paper No. 79-3087. Am. Soc. Agr. Engr.: St. Joseph, MI.

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

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

Paulsen, M.R., and T.L. Thompson. 1973. Effects of reversing the airflow in a cross-flow grain dryer. Trans. ASAE 16 (3): 541-545.

Peplinski, A.J., O.L. Brekke, E.L. Griffin, G.E. Hall, and L.D. Hill. 1975. Corn quality as influenced by harvest and drying conditions. Cereal Foods World 20: 145-149, 154.

Pierce, R.O., and T.L. Thompson. 1981. Energy use and performance related to cross-flow dryer design. Trans. ASAE 24 (1): 216-220.

Ross, I.J., and G.M. White. 1972. Discoloration and stress cracking of white corn as affected by overdrying. Trans. ASAE 15 (2): 327-329.

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

Sabbah, M.A., G.H. Foster, C.G. Haugh, and R.M. Peart. 1972. Effect of tempering after drying on cooling shelled corn. Trans. ASAE 15(4):763-765.

Schisler,I.P.1982.Personal comunication.

Shove, G.C., and E.F. Olver. 1967. Temperature gradients in drying grain. Trans. ASAE 10(2): 152-153-156.

Steffe, J.F., and R.P. Singh. 1980. Theoretical and practical aspects of rough rice tempering. Trans. ASAE 23 (3): 775-782.

Stephens, L.E., and G.H. Foster. 1976. Breakage tester predicts handling damage in corn. U.S. Agr. Res. Serv., ARS-NC-49, USDA, Washington, D.C., 6 pp.

The World Almanac and Book of Facts. 1981. Published by Newspaper Interprise Association, Inc. New York, NY.

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

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

Troeger, J.M., and W.V. Hukill. 1970. Mathematical description of the drying rate of fully exposed corn. ASAE Paper No. 70-324. Am. Soc. Agr. Engr.: St. Joseph, MI.

Westelaken, C.M. 1977. Concurrent-flow commercial grain dryers. The Westelaken models. ASAE Paper No. 77-3016, Am. Soc. Agr. Engr.: St. Joseph, MI.

Westelaken, C.M., and F.W. Bakker-Arkema. 1978. Concurrent flow grain dryind. CSAE Paper No. 78-0712. Annual Meeting of the Canadian Society of Agricultural Engineers: Regina, Saskatchewan, Canada.

White, G.M., and I.J. Ross. 1972. Discoloration and stress cracking in white corn as affected by drying temperature and cooling rate. Trans. ASAE 15 (3): 504-507.

White, G.M., and I.J. Ross. 1971. Moisture equilibrium in mixing of shelled corn. ASAE Paper No. 71-305. Am. Soc. Agr. Engr.: St. Joseph, MI.

APPENDICES

APPENDIX A

```
      PROGRAM XFLO(INPUT,OUTPUT,TAPE5=INPUT)
      COMMON/HELP/IHELP(1)
      DIMENSION KH(4)
C*****        MAIN PROGRAM FOR SIMULATION OF A CROSSFLOW DRYER
C*****    INPUT CONDITIONS OF DRYER TO BE SIMULATED
C*****     C R O S S F L O W   G R A I N   D R Y E R   M O D E L
C*****              F.W.BAKKER-ARKEMA, PROJECT LEADER
C*****    R.C.BROOK AND V.A.DALPASQUALE AND MARK HARDING,PROGRAMMERS
C*****
C*****
C*****                     M O D I F I E D
C*****
C*****                            By
C*****
C*****                      I.P. SCHISLER (1982)
C*****
C COMMON WITH LENGTH SET IN PAUXCYBER:=MAIN,PRESS,PRPRTY,HLATENT::
      COMMON/LSM/ZKNT
      LOGICAL ZKNT
       COMMON/MEIER/OTTEN,OM,OFLAG
      COMMON/MAIN/XMT,THT,RHT,DELT,CFM,XMO,KAB
      COMMON/BROOK/TOTEN,TOTH2O,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBTPR,XWIDE,PDE
      COMMON/PRPRTY/SA,CA,CV,CW,RHOP,CP
      COMMON/HLATENT/HA,HB,HFG
      COMMON/IFLAGS/JFLAG,ICON,THIGH,KVAD,JUAN,APR23
      COMMON /PRESS/PATM
      COMMON/NAMES/MDOT(4,3)
      COMMON/VEL/FL,FL1,KK2,XREL,KSTG,THZIN,VREL
      COMMON/CYCLE/XMOUT,SUMZT,HAVER,THOUT,BTUH2O
      COMMON/ARRAYS/XM(100),RH(100),T(100,2),H(100,2),TH(100,2),GA
      COMMON//XY,IADJ,IXY,SXMD,ADJ(6,1)
      EXTERNAL OPTH
      COMMON/HOPT/ REPNT,HI3,HI4,TI3,TI4,REUSE,TINE,HINE,VERIFY,FHIN,ATI
     1N,FATIN
      LOGICAL REUSE,REPNT,VERIFY,HELP,RMRK
      DATA TRN/0.001/, REPNT/.FALSE./, VERIFY/.FALSE./
      DATA KM20/ - 20/
      F(T) = T + 459.69
      VERIFY = .FALSE.
      KAB = 0
      ZKNT = .FALSE.
      DECODE (4,914,IHELP(KM20) )KH
      HELP = .FALSE.
```

```
      RMRK = .TRUE.
      IF (KH(1) .EQ. 1HH .AND. KH(2) .EQ. 1HE .AND. KH(3) .EQ. 1HL .AND.
     1 KH(4) .EQ. 1HP) HELP = .TRUE.
      IF (HELP) RMRK = .FALSE.
      IF (RMRK) CALL REMARK (40HOPTIONS EXPLAINED IF: ATTACH,HELP,XFLO.
     1)
      IF (RMRK) CALL REMARK (40HATTACH,P,PAUXCYBER. LIBRARY,P. HELP.
     1)
      REUSE = .FALSE.
    1 CONTINUE
      DELX = 0.1
      DELT = 0.002
      THZIN = 0.
      THIGH = 0.0
      YADD = 0.
      NSTG = 1
      KSTG = 1
      TOTEN = 0.
      TOTH20 = 0.
C IPS TOTEN,TOTH20 ARE CUMULATIVE WRT STAGES AND SEGMENTS
      FL = 0.0
      IF (HELP) PRINT 960
      IF (HELP) PRINT 933
      PRINT 938
      READ 926, STAGES
      PRINT 925, STAGES
      TB = STAGES
      PRINT 946
      READ 926, EQN
      PRINT 925, EQN
      IF (HELP) PRINT 950
      PRINT 901
      READ 926, PDE
      OFLAG = 0.
      IF (PDE .LT. 0.) OFLAG = 1.
      IF (PDE .LT. 0.) PDE = 0.
      PRINT 925, PDE
      IF (TB .LT. 0.) GO TO 10
      PRINT 923
      READ 926, PRODUCT
      PRINT 925, PRODUCT
      IPROD = INT(PRODUCT)
      CALL DATA (IPROD)
      IF (OFLAG .EQ. 1.) MDOT(3,2) = 10HOTTEN'SOYS
      IF (PDE .EQ. 0.) PRINT 927, (MDOT(I,IPROD),I=1,4)
      IF (PDE .NE. 0.) PRINT 927, (MDOT(I,3),I=1,4)
      IF (HELP .AND. PDE .EQ. 0.) PRINT 959
      IF (HELP .AND. PDE .NE. 0.) PRINT 961
      TB = 0.
    2 CONTINUE
      IF (HELP .AND. FL .EQ. 1.) PRINT 902
```

```
      KVAD = 0
      PRINT 917, NSTG
      PRINT 935
      READ 926, XWIDE
      IF (NSTG .EQ. 1) XVAD = XWIDE
      IF (NSTG .GE. 2 .AND. PDE .EQ. 1.) XWIDE = XVAD
C NOTE VARIABLE XWIDE ADJUSTED IN CONVERT EXCEPT VAD(.,.) FOR PDE=1.
      PRINT 925, XWIDE
      XWIDE = XWIDE/12.
C SET KO AND UL1 TO VALUE LAST PASS, SET KN
      KO = KN
      KN = 1 + INT((XWIDE+TRN)/DELX)
      IF (NSTG .GE. 2) UL1 = FL1
      PRINT 936
      READ 926, YLENG
      PRINT 925, YLENG
      PRINT 937
      READ 926, DBTPR
      PRINT 925, DBTPR
      IF (HELP) PRINT 958
      PRINT 903
      READ 926, XY
      IF (XY .NE. 1. .AND. XY .NE. 2. .AND. XY .NE. 3.) XY = 0.
      PRINT 925, XY
      IF (HELP) PRINT 904
      PRINT 932
      READ 926, BPH
      IF (BPH .LT. 0.) BPH = YLENG/(-BPH/60.)/1.244
      PRINT 925, BPH
      PRINT 934
      READ 926, TB
      PRINT 925, TB
      GVEL = BPH*1.244
      GP = GVEL*RHOP
      IF (HELP) PRINT 951
      PRINT 939
      READ 926, FM
C  FM (FINE MATTER) EITHER DOMAIN (0., 0.1) OR RESET IN CRSFLWJ
      PRINT 925, FM
      IF (FM .GE. 0.1 .OR. FM .LT. 0.) PRINT 951
      IF (HELP) PRINT 952
      PRINT 940
      IF (NSTG .EQ. 1) READ 926, HDF
      IF (HDF .EQ. 0.) HDF = 1.
C  IN LAYEQ AND LAYEQSO HDF EITHER DOMAIN (0.99 TO 1.) OR RESET TO 1.
      PRINT 925, HDF
      IF (PDE .EQ. 0. .AND. (HDF .GT. 1. .OR. HDF .LE. 0.99)) PRINT 952
      IF (PDE .NE. 0. .AND. HDF .NE. 1.) PRINT 953
      IF (NSTG .GE. 2) PRINT 930
      IF (NSTG .GE. 2) PRINT 918, THOUT
      IF (HELP .AND. NSTG .GE. 2) PRINT 954
```

```
      PRINT 930
      READ 926, THIN
C DEFAULT WHEN ZERO INPUT
      IF (THIN .EQ. 0.) THIN = THOUT
      PRINT 925, THIN
      IF (NSTG .GE. 2) PRINT 931
      IF (NSTG .GE. 2) XMO = 100.*XMS/(1.+XMS)
      IF (NSTG .GE. 2) PRINT 918, XMO
      IF (HELP .AND. NSTG .GE. 2) PRINT 954
      PRINT 931
      READ 926, XMOW
C DEFAULT WHEN ZERO INPUT
      IF (XMOW .EQ. 0.) XMOW = XMO
      PRINT 925, XMOW
      XMO = XMOW/(100.-XMOW)
      IF (NSTG .EQ. 1) OTTEN = XMO
      XMS = XMO
      IF (NSTG .EQ. 1) PRINT 924
      IF (NSTG .EQ. 1) READ 926, TAMB
      IF (NSTG .EQ. 1) PRINT 925, TAMB
      IF (NSTG .EQ. 1) PRINT 928
      IF (NSTG .EQ. 1) READ 926, RHAMB
      IF (RHAMB .GT. 1.) RHAMB = RHAMB/(10**(1+INT(ALOG10(RHAMB))))
      TY = RHAMB
      IF (NSTG .EQ. 1) PRINT 925, RHAMB
      HI = HADBRH(F(TAMB),RHAMB)
      IF (NSTG .EQ. 1) PRINT 944, HI
      XMT5 = XMO
      IF (NSTG .EQ. 1 .AND. PDE .NE. 0.) CALL DEPOT (5,D1,D2,XMT5,D4,D5)
      PRINT 919
      IF (HELP .AND. NSTG .GE. 2) PRINT 955
      IF (NSTG .GE. 2) PRINT 920, TIN1, TAMB
      READ 926, TIN
      IF (TIN .EQ. 1. .AND. NSTG .GE. 2) TINE = TAMB
C  ALTERNATE POINTER FOR FAN TEMPERATURE
      IF (TIN .EQ. 0. .AND. NSTG .GE. 2) TIN = TIN1
      IF (TIN .EQ. 1. .AND. NSTG .GE. 2) TIN = TAMB
      IF (TIN .EQ. 2. .AND. NSTG .GE. 2) TIN = SUMZT
      PRINT 925, TIN
      THIGH = AMAX1(THIN,TIN,THZIN)
      IF (NSTG .EQ. 1) TIN1 = TIN
C  IPS WHEN MULTIPLE STAGES THIS THIGH (SET ACCURATELY WITH THIN FROM
C  FROM LAST STAGE) IS NEEDED BY WBDBHAS IN SOLVE4 SO THAT ROOT
C  IS WITHIN GUESSES SENT TO  ZEROIN..
      IF (HELP .AND. NSTG .EQ. 1) PRINT 956
      IF (NSTG .EQ. 1) PRINT 943
      IF (NSTG .EQ. 1) READ 926, FUEL
      IF (FUEL .LT. 0.) REUSE = .TRUE.
      IF (REPNT) REUSE = .FALSE.
C RECYCLED IS 2 AND COOLED IS STAGE 3: IOP3 AND IOP4.
      IOP3 = 2
```

```
      IOP4 = 3
      IF (NSTG .EQ. 1) PRINT 925, FUEL
      IF (NSTG .EQ. 1 .AND. HELP) PRINT 905
      IF (NSTG .EQ. 1) CALL ABSH (HIN,TAMB,TIN,HI,FUEL)
      IF (NSTG .EQ. 1) GTINE = TINE
      IF (NSTG .EQ. 1) FHIN = HIN
      IF (NSTG .EQ. 1) HIN1 = HIN
      IF (HELP .AND. NSTG .GE. 2) PRINT 955
      IF (NSTG .GE. 2) PRINT 921, HIN1, HI
      IF (NSTG .GE. 2) READ 926, HIN
      IF (HIN .EQ. 1. .AND. NSTG .GE. 2) HINE = HI
C ALTERNATE POINTER FOR FAN HUMIDITY
      IF (HIN .EQ. 0. .AND. NSTG .GE. 2) HIN = HIN1
      IF (HIN .EQ. 1. .AND. NSTG .GE. 2) HIN = HI
      IF (HIN .EQ. 2. .AND. NSTG .GE. 2) HIN = HAVER
      IF (NSTG .GE. 2) PRINT 925, HIN
      APR23 = HIN
      PRINT 929
      READ 926, CFMBU
      PRINT 925, CFMBU
      CFM = CFMBU*XWIDE/1.244
      FL = 0.
      PRINT 947
      READ 926, FL1
      PRINT 925, FL1
      IF (FL1 .EQ. 0.) XREL = 1.
      IF (FL1 .EQ. 0.) VREL = 1.
      IF (FL1 .EQ. 1. .AND. FL .EQ. 0.) VREL = 1.
      TRY1 = 5.
C INTERPOLATES IN SUBROUTINE SUB AT FEWER THAN (TRY1) COMPUTED POINTS
      IADJ = 4 + INT(YLENG/(DELT*GVEL*TRY1*DBTPR))
      YADD = YLENG/FLOAT(IADJ-4)
      IF (XY .EQ. 0.) CALL SETFL (ADJ(6,IADJ))
      IF (FL1 .EQ. 0.0) GO TO 4
      PRINT 948
      READ 926, XREL
      PRINT 925, XREL
      XWIDE1 = XWIDE*XREL
      XWIDE2 = XWIDE - XWIDE1
      IND1 = INT((XWIDE1+TRN)/DELX) + 1
      KO1 = IND1
      GO TO 5
    3 FL = 1.
      PRINT 949
      KSTG = 2
      READ 926, VREL
      PRINT 925, VREL
      IND1 = INT((XWIDE2+TRN)/DELX) + 1
      KO2 = IND1
      GVEL = GVEL*VREL
      CALL UNMIX2 (KO,KN,KO1,KO2,UL1)
```

```
      IF (XY .NE. 0.) ADJ(1,1+IADJ) = XWIDE1
      GO TO 8
    4 IND1 = INT((XWIDE+TRN)/DELX) + 1
    5 CONTINUE
      RHIN = RHDBHA(F(TIN),HIN)
      RHT = AMAX1(0.,AMIN1(1.,RHIN))
C SET AIR INLET VALUES THAT DO NOT DEPEND ON UNMIX.
      DO 101  I = 1, IND1
        H(I,2) = HIN
        H(I,1) = HIN
        RH(I) = RHT
  101 CONTINUE
      IF (HELP .AND. NSTG .GE. 2) PRINT 957
      IF (NSTG .GE. 2) PRINT 942
      IF (NSTG .GE. 2) READ 926, RTYPE
      IF (NSTG .EQ. 1) RTYPE = 1.
      ITYPE = INT(RTYPE)
      IF (NSTG .GE. 2) PRINT 925, FLOAT(ITYPE)
      IF (NSTG .GE. 2) PRINT 906
      IF (NSTG .GE. 2) READ 926, UNMIX
      IF (NSTG .GE. 2) PRINT 925, UNMIX
      IF (NSTG .EQ. 1) UNMIX = 2.
      IF (NSTG .GE. 2 .AND. UNMIX .NE. 1.) UNMIX = 2.
C SET AIR INLET SIDE (DUAL) OR ALL TOP (SINGLE SPEED);AFTER IND1SET
      IF (UNMIX .EQ. 1.) GO TO 6
      DO 102  I = 1, IND1
        T(I,2) = THIN
        T(I,1) = T(I,2)
  102 CONTINUE
    6 CONTINUE
      IF (UNMIX .EQ. 2. .AND. RTYPE .EQ. 2. .AND. NSTG .GE. 2) CALL UNMI
     1X3 (KO,KN,KO1,KO2,UL1)
      IF (NSTG .GE. 2) CALL UNMIX1 (KO,KN,KO1,KO2,UL1)
      IF (UNMIX .EQ. 2. .AND. NSTG .GE. 2 .AND. PDE .EQ. 1. .AND. RTYPE
     1.EQ. 1.) CALL DEPOT (8,D1,D2,D3,D4,D5)
      IF (UNMIX .EQ. 2. .AND. NSTG .GE. 2 .AND. PDE .EQ. 1. .AND. RTYPE
     1.EQ. 2.) CALL DEPOT (4,D1,D2,D3,D4,D5)
      IF (UNMIX .EQ. 1. .AND. NSTG .GE. 2 .AND. PDE .EQ. 1. .AND. RTYPE
     1.EQ. 2.) CALL DEPOT (3,D1,D2,D3,D4,D5)
      IF (UNMIX .EQ. 1.) GO TO 7
C SET VALUES WHEN MIXED (INCLUDES TOP OF FIRST STAGE)
      DO 103  I = 1, IND1
        XM(I) = XMO
        IF (EQN .EQ. 1. .OR. EQN .EQ. 2.) TH(I,2) = T(I,2) = T(I,1) = TH
     1  IN
        IF (EQN .EQ. 3. .OR. EQN .EQ. 4.) TH(I,2) = THIN
        TH(I,1) = TH(I,2)
  103 CONTINUE
    7 CONTINUE
      IXY = 2 + INT(YLENG/DBTPR)
      IF (XY .NE. 0.) CALL SETFL (ADJ(6,IADJ+IXY*IND1))
```

```
      IF (XY .NE. 0.) ADJ(1,1+IADJ) = 0.
      IF (ITYPE .EQ. 2) CALL CONVERT (KO,KN,KO1,KO2,UL1)
C SET NODE AT AIR INLET AFETER MIXING/AIRREVERSAL
      TH(1,2) = TIN
      TH(1,1) = TH(1,2)
      T(1,2) = TH(1,1)
      T(1,1) = T(1,2)
C*****   CONVERT AIRFLOW TO LB/HR BEFORE VSDBHA(F(TAMB),HIN)
      GA = 60.*CFM/VSDBHA(F(TINE),HINE)
C **********
      CHTC = 0.363*(GA**0.59)
      IF (GA .LT. 500.) CHTC = 0.69*(GA**0.49)
C **********
C ESTIMATE FOR CHTC FROM MSUAESRR224. ACTUALLY NEAR 10.
    8 IF (XY .EQ. 0.) KADJ = IADJ
      IF (XY .NE. 0.) KADJ = IADJ + IXY*IND1
C*****   PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES
      PRINT 941, CFM, GA, XMO, BPH*VREL, BPH*VREL*XWIDE*XREL, GVEL
      IF (HELP) PRINT 907, IADJ, YADD, KADJ
      IF (IND1 .GE. 100) PRINT 922, IND1
      CALL CRSFLWJ (TIN,THIN,HIN,YADD,TAMB,EQN)
      KVAD = IND1 - 1
      IF (FL1 .EQ. 0.) FL = 1.
      IF (FL .EQ. 0.) GO TO 3
      IF (NSTG .EQ. IOP3) HLS = HI3
      IF (NSTG .EQ. IOP3) HI3 = HAVER
      IF (NSTG .EQ. IOP4) FHI4 = HI4
      IF (NSTG .EQ. IOP4) HI4 = HAVER
      IF (NSTG .EQ. IOP3) FTI3 = TI3
      IF (NSTG .EQ. IOP3) TI3 = SUMZT
      IF (NSTG .EQ. IOP4) FTI4 = TI4
      IF (NSTG .EQ. IOP4) TI4 = SUMZT
      IF (NSTG .GE. STAGES .AND. FL .EQ. 1.) GO TO 9
      KSTG = 1
      NSTG = NSTG + 1
C  IPS SIMULATE NEXT SPEED OR SECOND SIDE OF TWO-STAGE.
      GO TO 2
    9 PRINT 945, KAB
C  *****OPTION*****------------------------------------------
C  OPTION= ZEROIN CALCULATES LOCKSTEP RECYCLED TEMPERATURE AND HUMIDTY
      IF (FUEL .LT. 0. .OR. HELP) PRINT 909, FTI3, TI3
      IF (FUEL .LT. 0. .OR. HELP) PRINT 911, HLS, HI3
      IF (FUEL .LT. 0. .OR. HELP) PRINT 910, FTI4, TI4
      IF (FUEL .LT. 0. .OR. HELP) PRINT 908, FHI4, HI4
      VERIFY = .TRUE.
      IF (NSTG .GE. IOP3 .AND. .NOT. REPNT) CALL ABSH (HIN,TAMB,TIN,HI,F
     1UEL)
      VERIFY = .FALSE.
      IF (NSTG .GE. IOP3 .AND. .NOT. REPNT) PRINT 915, GTINE, ATIN
      IF (NSTG .GE. IOP3 .AND. .NOT. REPNT) PRINT 916, FHIN, HIN
      IF ( .NOT. REUSE .AND. .NOT. REPNT) STOP
```

```
      IF (REPNT) STOP
C     HLOW = 0.5*HI3
C     HHI = 1.75*HI3
C     EPS = 0.3*HI3
C     SAVE1=HHI
C     SAVE2=HLOW
C     CALL ZEROIN (HLOW,HHI,EPS,OPTH)
C     HIN = (HLOW+HHI)/2.
C     PRINT 935,HIN,SAVE2,SAVE1
      DO 104  J = 1, 5
        TI3 = 0.5*(FTI3+TI3)
        FTI3 = TI3
        HI3 = 0.5*(HLS+HI3)
        HLS = HI3
        FTI4 = 0.5*(TI4+FTI4)
        TI4 = FTI4
        FHI4 = 0.5*(HI4+FHI4)
        HI4 = FHI4
        DUMOBJ = OPTH(HLS)
  104 CONTINUE
      REPNT = .TRUE.
      REWIND 5
      KAB = 0
      GO TO 1
C *****OPTION*****-------------------------------------------
C OPTION= COMPARISON OF THINLAYER AND PDE MOISTURE REMOVAL
   10 CONTINUE
      DELT = 0.03
      PRINT 940
      READ 926, HDF
      PRINT 925, HDF
      OFLAG = 0.
C DELT , HDF, AND OFLAG CAN BE SET TO OTHER VALUES
      PRINT 923
      READ 926, PRODUCT
      PRINT 925, PRODUCT
      IPROD = INT(PRODUCT)
      CALL DATA (IPROD)
      PRINT 930
      READ 926, THIN
      PRINT 925, THIN
      PRINT 931
      READ 926, XMOW
      PRINT 925, XMOW
      PRINT 928
      READ 926, RHAMB
      PRINT 925, RHAMB
      XMT = XMOW/(100.-XMOW)
      XMT5 = XMT
      XMNOW = XMT5
      XMO = XMNOW
```

```
      OTTEN = XMO
      RHIN = RHAMB
      CALL DEPOT (5,D1,D2,XMT5,D4,D5)
      TB = -TB/60.
C HDF,RHT,THT,CFM,DELT (LAYEQ); JFLAG, F1, KVAD (DEPOT); GVEL (EMCPDE)
      TIME = 0.
      JFLAG = 1
      KVAD = 0
      GVEL = 1.
      F1 = DELX
      JFLAG = 1
      RHT = RHIN
      THT = THIN
      CFM = 0.
      HI = HADBRH(F(THIN),RHAMB)
      XME = EMC(RHAMB,THIN)
      PRINT 912, THIN, XMT, RHIN, TB, HI, XME
   11 TIME = TIME + DELT
      CALL DEPOT (6,RHIN,THIN,XMNOW,XMC,D5)
      CALL DEPOT (10,D1,D2,D3,D4,XMC)
      CALL DEPOT (11,F1,D2,D3,D4,D5)
      IF (IPROD .EQ. 1) CALL LAYEQ
      IF (IPROD .EQ. 2) CALL LAYEQSO
      PDE = XMC/(1.+XMC)
      TROGER = XMT/(1.+XMT)
      PRINT 913, TIME, PDE, TROGER
      XMNOW = XMC
      IF (TIME .LE. TB) GO TO 11
      STOP
C
  901 FORMAT (1X*PDE THINLAYER; N=0 Y=1 SH=2 :*)
  902 FORMAT (1X*------ IN SUMMARY TABLE*,/,1X*BTU/LB-H20 FOR SEGMENTS R
     1ELATES ENERGY TO WIDTH*,/,1X*STATIC PRESSURE ONLY DEPENDS ON WIDTH
     2 FOR SOYBEANS*)
  903 FORMAT (1X*XY; N=0 Y=1, NODE=2, SCAN=3:*)
  904 FORMAT (1X*IF BPH = NEGATIVE TIME (MIN) THEN BATCH CROSSFLOW*,/,5X
     1,*WITH ROWS IN OUTPUT TABLE BEING ZERO TO TOTAL HOLDING TIME*)
  905 FORMAT (1X*DOES DRYER? N=AMBIENT TO BURNER *,/,5X*Y=STAGE 2 RECYCL
     1ED AND STAGE 3 COOLER (EITHER ZERO LENGTH)*,/,1X*LENGTH (OR MORE C
     2ORRECTLY AIRFLOW) OF THREE STAGES*)
  906 FORMAT (1X*ARRAY AVERAGE THE TOP OF STAGE GRAIN MOISTURE ?*,/,1X*1
     1=NO CHANGE; 2= MAKE MOISTURE UNIFORM :*)
  907 FORMAT (1X*SETFL ADJ(6,*I3*) FOR EDGE EVERY*F10.4* FT**; ADJ(6,*I3
     1*) INCLUDING XY PRINTOUT*)
  908 FORMAT (1X*TAG ALONG: COOLER HUMIDITY*2(1X,E10.4))
  909 FORMAT (1X*TAG ALONG: RECYCLE TEMPERATURE*2(1X,E10.4))
  910 FORMAT (1X*TAG ALONG: COOLER TEMPERATURE*2(1X,E10.4))
  911 FORMAT (1X*TAG ALONG: RECYCLE HUMIDITY*2(1X,E10.4))
  912 FORMAT (/////,1X,*TH(F) M(DB) RH(DEC) TIME(HR) H EMC*,6(1X,E10.4))
  913 FORMAT (1X*TIME *E10.4* M BY PDE = *E10.4* M BY THINLAYER = *E10.4
     1)
```

```
914 FORMAT (4A1)
915 FORMAT (1X*TAG ALONG T TO BURNER ASSUMED:ACTUAL*2(1X,E10.4))
916 FORMAT (1X*TAG ALONG H FROM BURNER ASSUMED:ACTUAL*2(1X,E10.4))
917 FORMAT (1X* INPUT FOR STAGE=*I5)
918 FORMAT (1X,E10.4)
919 FORMAT (1X*INLET  AIR TEMP. (SAY,FROM HEATER),F:*)
920 FORMAT (1X*(TIN) EITHER HEATER OR AMBIENT*,/,3(1X,E10.4))
921 FORMAT (1X*(ABS.HUM.) EITHER HEATER OR AMBIENT*,/,3(1X,E10.4))
922 FORMAT (* WARNING ARRAYS TOO SMALL FOR X=X+DELX:MODE=1,IND1=*I4)
923 FORMAT (1X*TYPE OF PRODUCT(CORN=1 OR SOYBEAN=2):*)
924 FORMAT (5X*INLET AMBIENT TEMP, F :*)
925 FORMAT (1H+,40X,2F10.4,/,5(1X,F10.4))
926 FORMAT (5F10.2)
927 FORMAT (*OCROSSFLOW GRAIN DRYER SIMULATION*/* USING THE *A10,1X,A1
   10*  EQUATION FOR *A10/* AND EMC BY *A10//)
928 FORMAT (5X*AMBIENT REL HUM, DEC :*)
929 FORMAT (5X*AIRFLOW, CFM/BU (AT FAN INLET):*)
930 FORMAT (5X*INLET GRAIN TEMP, F:*)
931 FORMAT (5X*INLET MOISTURE, WET BASIS PERCENT:*)
932 FORMAT (5X*GRAINFLOW (BU/HR/SQ FT):*)
933 FORMAT (1X*IF NO. STAGES = NEGATIVE DRYING TIME (MIN)*,/,* COMPARE
   1S PDE TO TROGER:INITIAL M,THIN (SAY TIN) AND  RH*)
934 FORMAT (1X*RATIO VOL. TEMPER/VOL. INPUT;*)
935 FORMAT (5X*COLUMN WIDTH, IN:*)
936 FORMAT (5X*COLUMN LENGTH, FT:*)
937 FORMAT (5X*OUTPUT INTERVAL; FT:*)
938 FORMAT (5X*NO.OF STAGES(DRYER+COOLER),NOT TEMPER:*)
939 FORMAT (5X*FINE MATERIALS,DECIMAL:*)
940 FORMAT (5X*HYBRID FACTOR,DEC :*)
941 FORMAT (//* PRELIMINARY CALCULATED VALUES*//* AIRFLOW, CFM/SQ FT
   1           *F8.4/* DRY AIRFLOW RATE, LB/HR-FT2    *F8.4/* INLET MC
   2(DRY BASIS DECIMAL)    *F8.4/* GRAIN FLOW RATE, BUSHELS/HR-FT2*F8.
   34,/,1X*BU PER HR PER FT OF COLUMN WIDTH*F8.4,/* GRAIN FLOW RATE, F
   4T/HR          *F8.4,/)
942 FORMAT (1X*ARRAY CONVERSION TO REVERSE AIRFLOW*,/,1X*(1=NO CHANGES
   1 2=REVERSE AIRFLOW):*)
943 FORMAT (5X*TYPE OF FUEL USED (1=NO.2 FUEL*/5X,*2=NAT.GAS, 3=L.P.GA
   1S):*)
944 FORMAT (5X,*CALCULATED AMBIENT ABS HUM=*9X,F10.4)
945 FORMAT (5X,*THIS IS THE END OF CROSSFLOW (N CON AB) *I16)
946 FORMAT (5X,*NUMBER OF EQUATIONS IN THE SYSTEM*/5X,*(1= 3 EQ.-EXPL;
   1 2= 3 EQ.-IMPL*,/,5X*3= 4 EQ.-IMPL; 4= 4 EQ.-IMPL;X=G(X):*)
947 FORMAT (* IS THIS A TWO SPEED GRAIN FLOW STAGE?*/10X*  YES - 1.0
   1   NO - 0.0: *) -
948 FORMAT (5X*FRACTIONAL WIDTH,(IN DEC OF 1ST SIDE)*)
949 FORMAT (5X* VELOCITY 2ND-SIDE/1ST-SIDE(SAY DEC)*)
950 FORMAT (1X*PDE ZERO:THINLAYER TROEGER,THOMPSON (SABBAH)*,/,1X*PDE
   1POSITIVE: CRANK-LYKOV (HEAT EQN) FOR SPHERE*,/,1X*PDE=2 THEN CORN
   2SABBAH.LE.160 CHU.GT.160*,/,1X*IF PDE NEGATIVE THEN OTTEN THIN LAY
   3ER (FOR SOYS)*,/,1X*WITH PDE RESET TO ZERO*)
951 FORMAT (1X*FIND MATTER (0.,0.1) OR RESET 0.05 IN CRSFLWJ*)
```

```
  952 FORMAT (1X*EITHER HYBRID DRYING FACTOR (0.99,1.) OR *,/,1X*RESET T
     10 1 IN LAYEQ AND LAYEQSO*)
  953 FORMAT (1X*ENTERED HDF MULTIPLIES DIFF(USIVITY) IN DEPOT*)
  954 FORMAT (1X*ENTER PROMPT VALUE OR ZERO WHICH SELECTS PROMPT*)
  955 FORMAT (1X*ENTER ONE OF THREE PROMPTS OR ENTER 0.,1.,2. POINTER*)
  956 FORMAT (1X*FUEL (IF NEGATIVE ZEROIN; IF ZERO SPECIFY RECYCLED)*,/)
  957 FORMAT (1X*TYPICAL (REVERSE,UNMIX) FOR GRAIN PREVIOUS STAGE*,/,1X*
     1(AUGER = 12) (GRAVITY = 11) (GRAVITY-HC = 21) (INVERT:22)*,/,1X*IN
     2VERT: OTTEN 1980 CAN J AG ENG,VOL 22 PP 163*)
  958 FORMAT (1X*XY = 1 PRINTS AT EACH (X,Y); XY=2 ALSO INTERNAL M*)
  959 FORMAT (1X*COMPOSITE OF TWO LAYEQ P 49 RR 244*,/,1X*CORN: TROEGER
     180 TO 160 F; THOMPSON ABOVE 160 F*,/,1X*SOYS: OVERHULTS 100 TO 220
     2 F; 20 TO 33 WB*)
  960 FORMAT (1X*NO. STAGES IS STAGES NEEDING DETAILED DESCRIPTION*,/,1X
     1*TEMPERING HOPPER ONLY NEEDS VOLUME, THETA AND RH(AMBIENT)*)
  961 FORMAT (1X*INSTEAD OF ANALYTICAL THIN LAYER SOLVES PDE SPHERE*,/,1
     1X*USING METHOD BROOK:STEFFE AND DIFFUSIVITY SABBAH*,/,1X,* (M) FRO
     2M PDE EQUALS (M) FROM DH/DX=(-GP/GA)DM/DY  *)
      END
C***********************************************************************
      SUBROUTINE ABSH(HIN,TAMB,TIN,HI,FUEL)
      LOGICAL VERIFY,REPNT,REUSE
      COMMON/HOPT/ REPNT,HI3,HI4,TI3,TI4,REUSE,TINE,HINE,VERIFY,FHIN,ATI
     1N,FATIN
      DATA INPT/0/
      IF (INPT .EQ. 0) HTIN = TIN
      IF (VERIFY) ATIN = (A5*TAMB+B3*TI3+B4*TI4)/A6
      IF (VERIFY) AHI = (A5*HI+B3*HI3+B4*HI4)/A6
      IF (VERIFY) HIN = AHI + A*(1.+AHI)*CP*(HTIN-ATIN)
      IF (VERIFY) RETURN
C  IPS MODEL OF HUMIDITY ADDED BY HEATER USED BY XFLO AND OPT.
C*****
C*****  FUEL=1 STANDS FOR NO.2 FUEL
C*****  FUEL=2 STANDS FOR NATURAL GAS
C*****  FUEL=3 STANDS FOR LIQUID PROPANE GAS
C*****
      IF (INPT .EQ. 0) TI4 = TAMB
      IF (INPT .EQ. 0) HI4 = HI
      IFUEL = IABS(INT(FUEL))
      IF (IFUEL .EQ. 0) A = 0.
      IF (IFUEL .EQ. 1) A = 7.0143E - 5
      IF (IFUEL .EQ. 2) A = 8.175E - 5
      IF (IFUEL .EQ. 3) A = 7.593E - 5
      CP = 0.24
      HFUEL = A*(1.+HI)*CP*(TIN-TAMB)
      HIN = HI + HFUEL
      IF (INPT .EQ. 0) PRINT 901
      IF ( .NOT. VERIFY) READ 906, FLAG
      IF (INPT .EQ. 0) PRINT 905, FLAG
      IF (FLAG .NE. 1.) TI3 = TINE = TAMB
      IF (FLAG .NE. 1.) HI3 = HINE = HI
```

```
      IF (FLAG .NE. 1. .AND. INPT .EQ. 0) PRINT 903
      IF (IFUEL .EQ. 0) READ 906, HINE, TINE
      IF (FLAG .NE. 1. .AND. INPT .EQ. 0) PRINT 906, HINE, TINE
      IF (FLAG .NE. 1.) RETURN
      IF (INPT .EQ. 0) PRINT 909
      IF (INPT .EQ. 0) READ 906, A6
      IF (INPT .NE. 0) READ 906, D
      IF (INPT .EQ. 0) PRINT 910
      IF (INPT .EQ. 0) READ 906, B3
      IF (INPT .NE. 0) READ 906, D
      IF (INPT .EQ. 0) PRINT 911
      IF (INPT .EQ. 0) READ 906, B4
      IF (INPT .NE. 0) READ 906, D
      IF (INPT .EQ. 0) A6 = A6 + B3
      IF (INPT .EQ. 0) A5 = A6 - B3 - B4
      IF (INPT .EQ. 0 .AND. A5 .LT. 0.) B4 = A6 - B3
      IF (INPT .EQ. 0 .AND. A5 .LT. 0.) PRINT 902
      IF (INPT .EQ. 0 .AND. A5 .LT. 0.) A5 = 0.
      A5 = A5/A6
      B3 = B3/A6
      B4 = B4/A6
      A6 = 1.
      IF (INPT .EQ. 0) PRINT 908, HIN, HFUEL + HI*(1.-B3)+0.025*B3
      IF (INPT .EQ. 0) READ 906, HIN
      IF (INPT .NE. 0) READ 906, D
      IF (INPT .EQ. 0) PRINT 907, TAMB, B3*TIN+(1.-B3)*TAMB
      IF (INPT .NE. 0) READ 906, D
      IF (INPT .EQ. 0) READ 906, TINE
      IF (INPT .EQ. 0) T13 = (A6*TINE-A5*TAMB-B4*T14)/B3
      IF (INPT .EQ. 0 .AND. 0 .NE. LEGVAR(T13)) T13 = TAMB
      ATIN = (A5*TAMB+B3*T13+B4*T14)/A6
      IF ( .NOT. REPNT) HATIN = ATIN
      IF (REPNT) ATIN = HATIN
      TINE = ATIN
      IF (INPT .EQ. 0) H13 = (A6*(HIN-A*CP*(TIN-ATIN))/(1.+A*CP*(TIN-ATI
     1N))-(A5*HI+B4*H14))/B3
      IF (INPT .EQ. 0 .AND. 0 .NE. LEGVAR(H13)) H13 = HI
      AHI = (A5*HI+B3*H13+B4*H14)/A6
      HFUEL = A*(1.+AHI)*CP*(TIN-ATIN)
      IF ( .NOT. REPNT) HIN = AHI + HFUEL
      IF ( .NOT. REPNT) HHIN = HIN
      IF (REPNT) HIN = HHIN
      HINE = HIN
      IF ( .NOT. VERIFY) PRINT 903
      IF ( .NOT. VERIFY) PRINT 906, HINE, TINE
      IF (INPT .EQ. 0) PRINT 904, B3, B4, A5
      INPT = 1
      RETURN
C
  901 FORMAT (1X*DOES DRYER RECYCLE AIR ? 1=Y 0=N: *)
  902 FORMAT (1X*WARNING RESET COOLER LENGTH AND DELETED AMBIENT*)
```

```
  903 FORMAT (1X*--------*,/,1X,*ENERGY BALANCE BASED ON H AND T:*)
  904 FORMAT (1X*FRACTION TO BURNER : RECYCLED, COOLER, MAKEUP*,/,15X,3(
     11X,F10.2))
  905 FORMAT (1H+,40X,2F10.4,/,5(1X,F10.4))
  906 FORMAT (5F10.4)
  907 FORMAT (1X,F10.2,* TO SAY *,F10.2,*  T TO BURNER: *)
  908 FORMAT (1X,F10.4,* TO SAY*,F10.4,* H  FROM BURNER: *)
  909 FORMAT (1X*LENGTH STAGE AIR EXHAUSTED: *)
  910 FORMAT (1X*LENGTH STAGE AIR RECYCLED: *)
  911 FORMAT (1X*LENGTH STAGE GRAIN COOLED: *)
      END
C***********************************************************************
      SUBROUTINE CONVERT(KO,KN,KO1,KO2,FL1)
C IPS REVERSING SIDE HEATED AIR ENTERS  STAGE REDUCES DM(X,Y)/DX
C IPS ASAE72-829 AND TASAE-16-541-1973; CONVERT IS CALLED BY XFLO
C IPS I ASSUMED OLD DRIVER STORED VALUES AS IN UNMIX1 AND UNMIX2.
C FL1 (=UL1) WHETHER PREVIOUS STAGE SINGLE OR DUAL SPEED
C KO PREVIOUS X-NODE TOTAL
C KN CURRENT X-NODE TOTAL
C KO1 PREVIOUS AIR INLET X-NODE
C KO2 PREVIOUS AIR OUTLET X-NODES
C*****
      COMMON/ARRAYS/XM(100),RH(100),T(100,2),H(100,2),TH(100,2),GA
      COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBTPR,XWIDE,PDE
      IT = IND1 + 1
      IND05 = IND1/2
      DO 101  I = 1, IND05
        IT = IT - 1
        TEMP = XM(IT)
        XM(IT) = XM(I)
        XM(I) = TEMP
        TEMP = RH(IT)
        RH(IT) = RH(I)
        RH(I) = TEMP
        TEMP = T(IT,1)
        T(IT,1) = T(I,1)
        T(I,1) = TEMP
        TEMP = H(IT,1)
        H(IT,1) = H(I,1)
        H(I,1) = TEMP
        TEMP = TH(IT,1)
        TH(IT,1) = TH(I,1)
        TH(I,1) = TEMP
  101 CONTINUE
      RETURN
      ENTRY UNMIX2
C WHEN TWO SPEED STORE RESULTS FROM AIR INLETSIDE
      DO 102  I = 1, KO1
        II = 100 - KO1 + I
C NOTE DIMENSION OF COMMON/ARRAYS/ IS 100
        XM(II) = XM(I)
```

```
        TH(II,2) = TH(I,2)
  102 CONTINUE
      RETURN
      ENTRY UNMIX1
      IF (FL1 .EQ. 0.) GO TO 1
      IF ((KO1+KO2) .GE. 100) PRINT 901
C STORE VALUES IN CASE GRAIN UNMIXED BETWEEN STAGES
C IF LAST STAGE WAS TWO SPEED PUT AIR OUTLET DATA IN LARGE-INDEX
C AND STORED AIR INLET DATA IN SMALL-INDEX POSITION OF PRODUCT ARRAYS.
      DO 103  I = 1, KO2
        II = I + KO1
        XM(II) = XM(I)
        TH(II,2) = TH(I,2)
  103 CONTINUE
      DO 104  I = 1, KO1
        II = 100 - KO1 + I
        XM(I) = XM(II)
        TH(I,2) = TH(II,2)
  104 CONTINUE
    1 DO 105  I = 1, KN
C IPS ADJUST LOWER EDGE (NSTG-1) FOR NON-UNIFORM WIDTH COLUMN (NSTG)
        K = KO + (KN-I)*(1-KO)/(KN-1)
        RH(I) = XM(K)
        TH(I,1) = TH(K,2)
  105 CONTINUE
      DO 106  I = 1, KN
        XM(I) = RH(I)
        TH(I,2) = TH(I,1)
  106 CONTINUE
      RETURN
      ENTRY UNMIX3
      K100 = 100
      IF (FL1 .EQ. 0.) KO1 = KN
      IF (FL1 .EQ. 0.) K100 = KN
      IF (FL1 .EQ. 0.) GO TO 2
      AM = 0.
      AT = 0.
      DO 107  I = 1, KO2
        AM = AM + XM(I)
        AT = AT + TH(I,2)
  107 CONTINUE
      AM = AM/FLOAT(KO2)
      AT = AT/FLOAT(KO2)
      DO 108  I = 1, KO2
        XM(I) = AM
        TH(I,2) = AT
  108 CONTINUE
    2 AM = 0.
      AT = 0.
      DO 109  I = 1, KO1
        II = K100 - KO1 + I
```

```
        AM = AM + XM(II)
        AT = AT + TH(II,2)
  109 CONTINUE
      AM = AM/FLOAT(K01)
      AT = AT/FLOAT(K01)
      DO 110  I = 1, K01
        II = K100 - K01 + I
        XM(II) = AM
        TH(II,2) = AT
  110 CONTINUE
      RETURN
C
  901 FORMAT (1X*WARMNING ARRAYS IN SUBROUTINE CONVERT OVERWRITTEN*)
      END
C***************************************************************************
      SUBROUTINE CRSFLWJ(TIN,THIN,HIN,YADD,TAMB,EQN)
C CRSFLWJ CONTROLS 4-VERSIONS OF CROSSFLOW EQUATIONS (1 TEMPERING)
      DIMENSION REFT(2),LABT(2),PAST(4)
       COMMON/MEIER/OTTEN,OM,OFLAG
      COMMON/MAIN/XMT,THT,RHT,DELT,CFM,XMO,KAB
      COMMON/BROOK/TOTEN,TOTH20,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBTPR,XWIDE,PDE
      COMMON/PRPRTY/SA,CA,CV,CW,RHOP,CP
      COMMON/CYCLE/XMOUT,SUMZT,HAVER,THOUT,BTUH20
      COMMON/ARRAYS/XM(100),RH(100),T(100,2),H(100,2),TH(100,-2),GA
      COMMON//XY,IADJ,IXY,SXMD,ADJ(6,1)
      COMMON/HLATENT/HA,HB,HFG
      COMMON/IFLAGS/JFLAG,ICON,THIGH,KVAD,JUAN,APR23
      COMMON/PRESS/PATM
      LOGICAL VERIFY,REPNT,REUSE
      COMMON/HOPT/ REPNT,HI3,HI4,TI3,TI4,REUSE,TINE,HINE,VERIFY,FHIN,ATI
     1N,FATIN
      COMMON/VEL/FL,FL1,KK2,XREL,KSTG,THZIN,VREL
      EXTERNAL SOLVE4,SOLVE
      DATA PATM/14.3/, RHC/0.9998/, TRN/0.001/, UT/2.326/
      DATA HMIN/0.001/, TOTHP/0./
      F(T) = T + 459.69
      JUAN = INT(EQN)
      IXYT = 0
      IF (FL1 .EQ. 1. .AND. FL .EQ. 1.) GO TO 1
      ISTOP = 0
      IF (TB .GT. 0.) ISTOP = 1
    1 YL = 0.
      PRL = 0.0
      YADJ = 0.
      IF (FL .EQ. 0.) STEN = 0.
      IF (FL .EQ. 0.) STH20 = 0.
      SGEN = 0.
      SGH20 = 0.
      ITERCT = 0
      SUMZT = 0.
```

```
      IEXIT = 0
      KKK = 0
      HAVER = 0.0
      JFLAG = 1
C*****     BEGIN TIME LOOP
      DELY = GVEL*DELT
C*****
C*****     BEGIN Y.-DEPTH LOOP
C*****
    2 YL = YL + DELY
      KAB = KAB + 100000000
C*****
C*****     COMPUTE MC FOR DEPTH=0
C*****
      IF (FL .EQ. 1.0) GO TO 3
C BEFORE (XFOVEL) TH(1,1)=(5.*TH(1,1)+T(1,1))/6. FOR ALL Y.
C BEFORE (XFLOSILVA) TH(1,1)=TIN
      TH(1,2) = TIN
      ALPHA = 2.*GA/555.
      ALPHA = AMIN1(1.,ALPHA)
      TH(1,2) = ALPHA*TIN + (1.-ALPHA)*TH(2,2)
      TH(1,1) = TH(1,2)
      THT = TH(1,1)
      XMT = XM(1)
      RHT = RHDBHA(F(T(1,1)),H(1,1))
      RH(1) = RHT
      IF (IPROD .EQ. 1 .AND. PDE .NE. 1.) CALL LAYEQ
      IF (IPROD .EQ. 2 .AND. PDE .NE. 1.) CALL LAYEQSO
      JFLAG = 1
      RHT5 = RHT
      THT5 = THT
      XMT5 = XMT
      IF (PDE .EQ. 1.) CALL DEPOT (6,RHT5,THT5,XMT5,XMC,D5)
      IF (PDE .EQ. 1.) CALL DEPOT (10,D1,D2,D3,D4,XMC)
      IF (PDE .EQ. 1.) XMT = XMC
      XM(1) = XMT
      H(1,2) = H(1,1)
      T(1,2) = T(1,1)
      TH(1,2) = TH(1,1)
      GO TO 4
C IPS INTERPOLATE TO GET INLET CONDITIONS ALONG EDGE OF SECOND SEGMENT.
    3 CALL SUB (KK2,YL-DELY,X,1,1)
      MSUB = INT(X)
      CALL SUB (MSUB,YL-DELY,XT,3,2)
      IF (YL .EQ. DELY) TIN = XT
      T(1,1) = XT
      CALL SUB (MSUB,YL-DELY,XTH,2,2)
      TH(1,1) = XTH
      CALL SUB (MSUB,YL-DELY,XH,5,2)
      H(1,1) = XH
      IF (YL .EQ. DELY) HIN = XH
```

```
      CALL SUB (MSUB,YL-DELY,XRH,6,2)
      RH(1) = XRH
      CALL SUB (MSUB,YL-DELY,XXM,4,2)
      XM(1) = XXM
      CALL SUB (KK2,YL,X,1,1)
      MSUB = INT(X)
      CALL SUB (MSUB,YL,XT,3,2)
      T(1,2) = XT
      CALL SUB (MSUB,YL,XTH,2,2)
      TH(1,2) = XTH
      CALL SUB (MSUB,YL,XH,5,2)
      H(1,2) = XH
      IF (YL .GT. DELY) GO TO 4
C NEED TO RESET AT LEAST TOP OF SECOND SIDE ;OTHERWISE
C DEFAULTS TO USING VALUES FROM BOTTOM FIRST SIDE OF STAGE.
      DO 101  J = 1, IND1
        RH(J) = RH(1)
        TH(J,2) = TH(1,2)
        TH(J,1) = TH(1,1)
        T(J,2) = T(1,2)
        T(J,1) = T(1,1)
        XM(J) = XM(1)
        H(J,2) = H(1,2)
        H(J,1) = H(1,1)
  101 CONTINUE
    4 CONTINUE
      IF (JUAN .EQ. 1) GO TO 7
      IF (JUAN .EQ. 4) GO TO 5
      IF (JUAN .EQ. 2 .OR. JUAN .EQ. 3) GO TO 9
C *****OPTION*****-------------------------------------------
C START CRSFLW2=(CRSFLW4 IN OPTXFLO AND XFLOVEL)
C              CROSSFLOW; 4-EQUATION IMPLICIT, ONE ITERATION IN SOLVE4.
C METHOD USED XFLOVEL (PADUCAH), OPTXFLO AND 7JIMXLFO(SAGINAW)
C *****OPTION*****-------------------------------------------
    5 DO 102  J = 2, IND1
        KAB = KAB + 100000000
        JFLAG = J
        JM = J - 1
C BEFORE  TH(J,2)=TH(JM,2) BY X RATHER THAN USUAL Y (XFLOVEL)
        CON1 = GA*DELT
        CON2 = CW - CV
        HFG = HEATLAT(XM(J),TH(J,1))
        CON3 = HFG + 212.*(CW-CV)
        CON4 = RHOP*DELX
        T1 = CON1*(H(J,1)-H(JM,1))
        T2 = CON1*(CA+CV*H(JM,1))
        IF (IPROD .EQ. 2) CP = 0.39123 + 0.46057*XM(J)
        T3 = CON4*(CP+CW*XM(J))
        T(J,2) = (-T1*CON3+T2*T(JM,1)+T3*TH(J,1))/(-T1*CON2+T2+T3)
        TH(J,2) = T(J,2)
C ESTIMATE OF HJ2 AS IN XFLOVEL
```

```
      HJ2 = H(JM,2)
      DIFF = SOLVE4(HJ2)
      IF (ICON .NE. 0) GO TO 6
C BEFORE ITERATED WITHIN SOLVE4 RATHER THAN TWO CALLS FROM CRSFLWJ
C BY TWO CALLS FROM CRSFLWJ ; SOLVE4 CAN BE USED BY ZEROIN4
C SUGGESTION:  NEWTON-RAPHSON SEARCH, LET HJ2=H,DIFF=D THEN
C H=(H1+H2)/2 - (D2-D1)/(H2-H1)*(D1+D2)
      CCON6 = GA*DELT/(RHOP*DELX)
      XMT = DIFF + XM(J) - (HJ2-H(JM,2))*CCON6
C RESET XMT BECAUSE RESET IN SOLVE4 BUT NOT IN ITERATIVE SOLVE4.
      HJ2 = H(JM,2) + (XM(J)-XMT)/CCON6
      DIFF = SOLVE4(HJ2)
    6 XM(J) = XMT
      IF (ICON .NE. 0) KAB = KAB + 10000
      XTEM = XM(J)
      THT5 = T(J,2)
      RHT5 = RH(J)
      XMT5 = XM(J)
      IF (PDE .EQ. 1.) CALL DEPOT (9,RHT5,THT5,XMT5,D4,XTEM)
  102 CONTINUE
      GO TO 23
C *****OPTION*****-------------------------------------------
C 3-EQUATION EXPLICIT (CRSFLW1) VALID LOW AIR FLOW
C METHOD USED UCRSOPT(TELPLAN), CCRS (PURDUE), SILVAXFLO (KJ/KG)
C *****OPTION*****-------------------------------------------
    7 DO 103  J = 2, IND1
      KAB = KAB + 10000000
      JFLAG = J
      JM = J - 1
      THT = T(J,2)
      XMT = XM(J)
      HFG = HEATLAT(XMT,THT)
      IF (H(J,1) .LE. 0.) H(J,1) = APR23
      IF (H(J,1) .GE. 1.) H(J,1) = 1.
      RHT = RHDBHA(F(T(J,1)),H(J,1))
C*****  CALL SUBROUTINE CONTAINING M EQUATION (M IS GRAIN MOISTURE)
      IF (IPROD .EQ. 2 .AND. PDE .NE. 1.) CALL LAYEQSO
      IF (IPROD .EQ. 1 .AND. PDE .NE. 1.) CALL LAYEQ
      RHT5 = RHT
      THT5 = THT
      XMT5 = XMT
      IF (PDE .EQ. 1.) CALL DEPOT (6,RHT5,THT5,XMT5,XMC,D5)
      IF (PDE .EQ. 1.) XMT = XMC
C*****  COMPUTE CONSTANTS USED BY EQUATIONS WITHIN LOOP
      CON1 = GA*DELT
      CON2 = CW - CV
      CON12 = CON1*CON2
      CON3 = HFG + 212.*(CW-CV)
      CON13 = CON1*CON3
      CON4 = RHOP*DELX
      CON5 = CON4/CON1
```

```
      CON6 = CON1/CON4
C*****  H EQUATION
      H(J,2) = H(JM,2) - CON5*(XMT-XM(J))
C*****  T EQUATION
      T1 = CON1*(H(J,1)-H(JM,1))
      T2 = CON1*(CA+CV*H(JM,1))
      IF (IPROD .EQ. 2) CP = 0.39123 + 0.46057*XMT
      T3 = CON4*(CP+CW*XM(J))
      T(J,2) = (-T1*CON3+T2*T(JM,1)+T3*THT)/(-T1*CON2+T2+T3)
C*****  COMPUTE RH AND CHECK FOR CONDENSATION
      IF (H(J,2) .LE. 0.) H(J,2) = APR23
      RH(J) = RHDBHA(F(T(J,2)),H(J,2))
      ICON = 0
      IF (RH(J) .LT. RHC) GO TO 8
C*****  CONDENSATION SIMULATOR
      ICON = 1
      IF (ICON .NE. 0) KAB = KAB + 10000
      TS = T(J,2)
      HS = HADBRH(F(TS),RHC)
      DHDT = HS - HADBRH(F(TS)-1.,RHC)
C*****  RE-EVALUATE M AND THETA USING MASS AND ENERGY BALANCES
      T1 = HS - H(JM,2) - DHDT*TS
      A = CON12*DHDT
      B = CON12*T1 - T2 - T3 - CON13*DHDT
      C = T2*T(JM,2) + T3*THT - CON13*T1
      T(J,2) = (-B-SQRT(B*B-4.*A*C))/(2.*A)
      H(J,2) = HS + DHDT*(T(J,2)-TS)
      IF (H(J,2) .LE. 0.) H(J,2) = APR23
      IF (H(J,2) .GE. 1.) H(J,2) = 1.
      RH(J) = RHDBHA(F(T(J,2)),H(J,2))
      XMT = XM(J) - CON6*(H(J,2)-H(JM,2))
      XMT5 = XMT
      XTEM = XM(J)
      RHT5 = AMAX1(0.,AMIN1(1.,RH(J)))
      THT5 = T(J,2)
    8 XM(J) = XMT
      TH(J,2) = T(J,2)
C IPS ADDED THETA EQUATION ; EQUATED SINCE LOW AIR FLOW RATE (GA).
      RH(J) = AMAX1(0.,AMIN1(1.,RH(J)))
      XMT5 = XM(J)
      RHT5 = RH(J)
      THT5 = TH(J,2)
      XTEM = XM(J)
      IF (PDE .EQ. 1.) CALL DEPOT (9,RHT5,THT5,XMT5,D4,XTEM)
  103 CONTINUE
     RHK = 100.*RH(IND1)
     GO TO 23
    9 CONTINUE
C *****OPTION*****---------------------------------------
C EITHER 3-EQUATION IMPLICIT (CRSFLW3) OR 4-EQUATION IMPLICIT (CRSFLW4)
C *****OPTION*****---------------------------------------
```

```
      DO 104  J = 2, IND1
        KAB = KAB + 100000000
        JFLAG = J
        JM = J - 1
        THT = TH(J,2)
        XMT = XM(J)
        HFG = HEATLAT(XMT,THT)
        IF (H(J,1) .LE. 0.) H(J,1) = APR23
        IF (H(J,1) .GE. 1.) H(J,1) = 1.
        RHT = RHDBHA(F(T(J,1)),H(J,1))
C*****
C*****     USE PREVIOUS X-VALUE OF H AS INITIAL GUESS
C*****
        HJ2 = H(JM,2)
        IF (JUAN .EQ. 2) DIFF = SOLVE(HJ2)
        IF (JUAN .EQ. 3) DIFF = SOLVE4(HJ2)
        XM(J) = XMT
        OM = XMT
C*****
C*****     CHECK CONDENSATION FLAG
C*****
        IF (ICON) 10, 10, 22
C*****
C*****     SET LIMITS ON H
C*****
   10   IF (DIFF) 15, 22, 11
C*****
C*****     CASE-1 SOLVING FOR ABSORPTION CONDITIONS (WRT EQ-14)
C*****
   11   RHLOW = 0.95*RH(J)
C*****
C*****     CHECK FOR FEASIBLE RHLOW
C*****
   12   IF (IPROD .EQ. 1) EQUIL = EMC(RHLOW,THT)
        IF (IPROD .EQ. 2) EQUIL = SOYEMC(RHLOW,THT)
        IF (XMT-EQUIL) 13, 14, 14
C*****
C*****     DECREASE RHLOW UNTIL XMT.GT.EQUIL
C*****
   13   RHLOW = 0.95*RHLOW
        GO TO 12
   14   HLOW = HADBRH(F(THT),RHLOW)
        HHI = H(J,2)
        GO TO 21
C*****
C*****     CASE-2 SOLVING FOR DRYING CONDITIONS (WRT EQ-13)
C*****
   15   HLOW = H(J,2)
C*****
C*****     CHECK FOR SUPERSATURATED CONDITIONS
C*****
```

```
      IF (IPROD .EQ. 2) EQUIL = SOYEMC(RHC,THT)
      IF (IPROD .EQ. 1) EQUIL = EMC(RHC,THT)
      IF (XMT-EQUIL) 17, 16, 16
   16 HHI = HADBRH(F(THT),RHC)
      GO TO 21
   17 RHHI = 0.5*(1.+RH(J))
C*****
C*****   CHECK FOR (NON-SUPERSATURATION) FEASIBLE RHHI
C*****
   18 IF (IPROD .EQ. 2) EQUIL = SOYEMC(RHHI,THT)
      IF (IPROD .EQ. 1) EQUIL = EMC(RHHI,THT)
      IF (EQUIL-XMT) 19, 20, 20
C*****
C*****   INCREASE RHHI UNTIL EQUIL.GT.XMT
   19 RHHI = 0.5*(1.+RHHI)
      GO TO 18
   20 HHI = HADBRH(F(THT),RHHI)
C*****
C*****   INITIATE SEARCH FOR TH,H,XM
C*****
   21 IF (JUAN .EQ. 2) HLOW = HLOW/4.
      IF (JUAN .EQ. 2) CALL REFALSI (HLOW,HHI,0.0001,SOLVE,H(J,2))
      IF (JUAN .EQ. 3) CALL ZEROIN4 (HLOW,HHI,0.001,SOLVE4)
C IPS CASE-3 ACCEPT INITIAL ESTIMATE (ICON CONDENSATION SOLVE:SOLVE4)
   22 XM(J) = XMT
      IF (ICON .NE. 0) KAB = KAB + 10000
      IF (H(J,2) .GT. 1.) H(J,2) = 1.
C*****
      IF (JUAN .EQ. 2) TH(J,2) = T(J,2)
C*****   END X-WIDTH LOOP
C*****
      XMT5 = XMT
      RHT5 = RHT
      THT5 = THT
      XTEM = XM(J)
      IF (PDE .EQ. 1.) CALL DEPOT (9,RHT5,THT5,XMT5,D4,XTEM)
  104 CONTINUE
C *****END OPTIONS*****-------------------------------------------
   23 CONTINUE
C * * * * * CRSFLW-CRSFLW2-CRSFLW3-CRSFLW4 SOLUTIONS HAVE BEEN FOUND
C *****END OPTIONS*****-------------------------------------------
    DO 105  LM = 1, IND1
C IPS ADDED TH(J,.)EQUATION
      TH(LM,1) = TH(LM,2)
      T(LM,1) = T(LM,2)
      H(LM,1) = H(LM,2)
      IF (IEXIT .EQ. 1) GO TO 105
      IF (LM .EQ. IND1 .AND. FL .EQ. 0.0) GO TO 24
      GO TO 105
C IPS STORE FIRST PASS WHEN X-POINT IS AT  TWO-SPEED INTERFACE.
   24 IF (YL .GE. YLENG) GO TO 25
```

```
      IF (YL .LT. YADJ) GO TO 105
   25 KKK = KKK + 1
      YADJ = YADJ + YADD
      ADJ(3,KKK) = T(LM,2)
      ADJ(2,KKK) = TH(LM,2)
      ADJ(1,KKK) = YL
      ADJ(5,KKK) = H(LM,2)
      ADJ(6,KKK) = RH(LM)
      ADJ(4,KKK) = XM(LM)
  105 CONTINUE
      RHK = 100.*RH(IND1)
      ITERCT = ITERCT + 1
      SUMZT = SUMZT + T(IND1,1)
      HAVER = HAVER + H(IND1,1)
C*****
C*****     CHECK IF LONG ENOUGH (OR DRY ENOUGH) OR TIME TO SAVE VALUES
C***** FOR PRINTING. IF NONE OF THESE GO TO THE BEGINNING OF THE LOOP
C*****
      IF (YL .GE. YLENG) GO TO 26
      IF (YL-PRL) 2, 27, 27
C*****
C*****     SET FLAG IF EXIT CONDTION MET.
C*****
   26 IEXIT = 1
      KK2 = KKK
C*****
C ***** COMMON OPTION *****---------------------------------------
C*****     MAKE FINAL CALCULATIONS AND STORE APPROPRIATE VALUES.
C ***** COMMON OPTION *****---------------------------------------
C*****
   27 PRL = PRL + DBTPR
      IXYT = IXYT + 1
      CALL CRSPR (YL,XMAVE,THAVE,RHK,XMEINW)
      IF (IEXIT .NE. 1) GO TO 2
C IPS COMPUTES THERMAL ENERGY USAGE FOR SEGMENT OF STAGE
      IF (FL .EQ. 0.) EINPUT = GA*(CA+CV*HINE)*(TIN-TINE)*YLENG
      WATER = (XMS-XMAVE)*RHOP*GVEL
      IF (FL .EQ. 0.) WATER = XREL*XWIDE*WATER
      IF (FL .EQ. 1.) WATER = (1.-XREL)*XWIDE*WATER
      IF (FL .EQ. 0.) ENERGY = XREL*EINPUT
      IF (FL .EQ. 1.) ENERGY = (1.-XREL)*EINPUT
      IF (WATER .NE. 0.) BTUH2O = ENERGY/WATER
      IF (WATER .EQ. 0.) BTUH2O = 0.
      SUMZT = SUMZT/FLOAT(ITERCT)
      HAVER = HAVER/FLOAT(ITERCT)
      TOTEN = TOTEN + ENERGY
      TOTH2O = TOTH2O + WATER
      TOTBTUW = TOTEN/TOTH2O
      STEN = STEN + ENERGY
      STH2O = STH2O + WATER
      SGEN = SGEN + ENERGY
```

```
      SGH2O = SGH2O + WATER
      A1 = STH2O - SGH2O
      A2 = STEN/STH2O
      A3 = SGEN/SGH2O
      IF (A1 .EQ. 0.) A4 = 0.
      IF (A1 .NE. 0.) A4 = (STEN-SGEN)/A1
      X22 = XMAVE/(1.+XMAVE)
      IF (A1 .NE. 0.) X11 = XMOUT/(1.+XMOUT)
      IF (A1 .EQ. 0.) X11 = 0.
      IF (FL .EQ. 1.) X12 = (XMOUT*XREL+XMAVE*(1.-XREL)*VREL)/(XREL+(1.-
     1XREL)*VREL)
C IPS X12=VOLUME AVERAGED MOISTURE CONTENT DRY BASIS.
      IF (FL .EQ. 0.) X12 = XMAVE
      IF (FL1 .EQ. 0.) XMS = X12
      IF (FL .EQ. 1.) XMS = X12
      X12 = X12/(1.+X12)
      IF (FL .EQ. 0.) THOUT = THAVE
      IF (FL .EQ. 1.) THOUT = (THOUT*XREL+THAVE*(1.-XREL)*VREL)/(XREL+(1
     1.-XREL)*VREL)
      IF (FL .EQ. 0.) XMOUT = XMAVE
      IF (FL .EQ. 0.) XMAVG = XMAVE
      IF (FL .EQ. 1.) XMAVG = (XMAVG*XREL+XMAVE*(1.-XREL)*VREL)/(XREL+(1
     1.-XREL)*VREL)
      IF (FL1 .EQ. 1. .AND. FL .EQ. 0.) C2 = THAVE
      IF (FL .EQ. 1.) C3 = THOUT
      IF (FL1 .EQ. 0.) C1 = C3 = THOUT
      IF (FL1 .EQ. 0.) C2 = 0.
      IF (FL .EQ. 1.) C1 = THAVE
      IF (IPROD .EQ. 2) GO TO 30
      QA = CFM*0.005075
C IPS COMPUTES STATIC PRESSURE AND RELATED MECHANICAL ENERGY USAGE
      IF (FM .LT. 0. .OR. FM .GT. 0.1) FM = 0.05
      IF (CFM .LE. 0.) GO TO 30
      IF (CFM-40.) 28, 29, 29
   28 SP = 1.2239183E - 3*(20529.535*QA**2/ALOG(1.+30.597*QA)+(14.5566-2
     16.418*QA)*FM)
      GO TO 31
   29 SP = 1.2239183E - 3*(436.667*QA+7363.038*QA**2+22525.819*QA*FM)
      GO TO 31
   30 SP = XWIDE*(CFM/75.2)**1.431
   31 POWER = SP*CFM/(6350.*0.5)*YLENG
      IF (FL1 .EQ. 0.) TOTHP = TOTHP + POWER
      IF (FL1 .EQ. 1. .AND. FL .EQ. 1.) TOTHP = TOTHP + POWER
      IF ( .NOT. REUSE) PRINT 906, SUMZT, HAVER, WATER, XMEINW
      IF ( .NOT. REUSE .AND. (FL1 .EQ. 0. .OR. (FL1 .EQ. 1 .AND. FL .EQ.
     1 1.))) PRINT 907, GA, SP, POWER, TOTHP
      IF ((FL .EQ. 1. .OR. FL1 .EQ. 0.) .AND. KSTG .EQ. 1) X11 = A1 = C2
     1 = 1.E13
      IF ((FL .EQ. 1. .OR. FL1 .EQ. 0.) .AND. .NOT. REUSE) PRINT 905, NS
     1TG, KSTG, X22, X11, X12, SGH2O, A1, STH2O, TOTH2O, A2, TOTBTUW, UT
     2*A2,UT*TOTBTUW
```

```
      IF ((FL .EQ. 1. .OR. FL1 .EQ. 0.) .AND. .NOT. REUSE) PRINT 914, EI
     INPUT, C1, C2, C3
C ***** COMMON OPTION *****-------------------------------------------
      IF (XY .EQ. 0.) GO TO 33
      IF (REUSE) GO TO 33
C ***** COMMON OPTION *****-------------------------------------------
      JXY = MINO(IXY,IXYT)
C SCAN TO FIND EXPOSURE TIME TO TEMPERATURE THRESHOLDS (QUALITY)
      LABT(1) = 10HGERMINATE
      LABT(2) = 10HBREAKAGE
      REFT(1) = 100.
      REFT(2) = 150.
      I5 = 4
      I6 = 2
      DO 113  I1 = 1, I6
        K1 = 0
        K2 = 0
        DO 107  I2 = 1, JXY
          ICLEAN = I2*IND1 - IND1 + IADJ
          DO 106  I3 = 1, IND1
            K2 = K2 + 1
            IF (REFT(I1) .LE. ADJ(2,I3+ICLEAN)) K1 = K1 + 1
  106     CONTINUE
  107   CONTINUE
        PRINT 901, 100.*FLOAT(K1)/FLOAT(K2),REFT(I1),LABT(I1)
        DO 108  I4 = 1, I5
          PAST(I4) = 0.
  108   CONTINUE
        DO 111  I3 = 1, IND1
          K3 = 0
          DO 109  I2 = 1, JXY
            ICLEAN = I2*IND1 - IND1 + IADJ
            IF (REFT(I1) .LE. ADJ(2,I3+ICLEAN)) K3 = K3 + 1
  109     CONTINUE
          DO 110  I4 = 1, I5
            IF (K3 .GE. I4*JXY/I5) PAST(I5-I4+1) = PAST(I5-I4+1) + 1.
  110     CONTINUE
  111   CONTINUE
        DO 112  I4 = 1, I5
          PRINT 902, FLOAT(100*K1)*PAST(I4)/FLOAT(IND1*K2)
     1          ,YLENG/(FLOAT(I4)*VREL*GVEL),(I5-I4+1),I5
  112   CONTINUE
  113 CONTINUE
      IF (XY .EQ. 3.) GO TO 33
C XY-PRINTOUT OF T,TH,H,RH,M.
      PRINT 908, (ADJ(1,J+IADJ),J=1,IND1)
      DO 114  I = 1, JXY
        ICLEAN = I*IND1 - IND1 + IADJ
        PRINT 913, (ADJ(3,J+ICLEAN),J=1,IND1)
  114 CONTINUE
      IF (JUAN .EQ. 1 .OR. JUAN .EQ. 2) GO TO 32
```

```
      PRINT 909, (ADJ(1,J+IADJ),J=1,IND1)
      DO 115  I = 1, JXY
        ICLEAN = I*IND1 - IND1 + IADJ
        PRINT 913, (ADJ(2,J+ICLEAN),J=1,IND1)
  115 CONTINUE
   32 CONTINUE
      PRINT 910, (ADJ(1,J+IADJ),J=1,IND1)
      DO 116  I = 1, JXY
        ICLEAN = I*IND1 - IND1 + IADJ
        PRINT 913, (ADJ(5,J+ICLEAN),J=1,IND1)
  116 CONTINUE
      PRINT 911, (ADJ(1,J+IADJ),J=1,IND1)
      DO 117  I = 1, JXY
        ICLEAN = I*IND1 - IND1 + IADJ
        PRINT 913, (ADJ(6,J+ICLEAN),J=1,IND1)
  117 CONTINUE
      PRINT 912, (ADJ(1,J+IADJ),J=1,IND1)
      DO 118  I = 1, JXY
        ICLEAN = I*IND1 - IND1 + IADJ
        PRINT 913, (ADJ(4,J+ICLEAN)/(1.+ADJ(4,J+ICLEAN)),J=1,IND1)
  118 CONTINUE
C X-PRINTOUT OF M WITHIN KERNEL FOR Y ACROSS BOTTOM OF STAGE.
      F1 = DELX
      DO 119  I = 1, IND1
        JFLAG = I
        IF (PDE .EQ. 1 .AND. XY .EQ. 2.) CALL DEPOT (11,F1,D2,D3,D4,D5)
  119 CONTINUE
   33 IF (ISTOP .EQ. 0 .AND. FL1 .EQ. 1 .AND. FL .EQ. 0.) RETURN
      IF (ISTOP .EQ. 1 .AND. FL1 .EQ. 0.) GO TO 34
      IF (ISTOP .EQ. 1 .AND. FL1 .EQ. 1. .AND. FL .EQ. 1.) GO TO 34
      RETURN
C ***** COMMON OPTION *****-------------------------------------
C SET PARAMETERS FOR END OF SECTION TEMPERING UNIT.
C ***** COMMON OPTION *****-------------------------------------
   34 CONTINUE
      ISTOP = 2
      RHAMB = AMAX1(0.,AMIN1(TY,RHC))
      IF (FL .EQ. 0.) GVEL = BPH*1.244
      IF (FL .EQ. 1.) GVEL = BPH*1.244*(XREL+(1.-XREL)*VREL)
      TY = YLENG/GVEL
C TY  TIME INPUT, TB (WAS VOL,NOW) TIME HOPPER,GVEL AVG FLOW RATE INPUT
      TB = TB*TY
      ABPH = GVEL/1.244
      IF ( .NOT. REUSE) PRINT 904, ABPH, TB
      CFM = 0.
      GA = 0.
      INDS = INT((XWIDE+TRN)/DELX) + 1
      HJ2 = HADBRH(F(THOUT),RHAMB)
      DO 120  J = 1, INDS
        T(J,1) = THOUT
        T(J,2) = THOUT
```

```
        TH(J,1)  = THOUT
        TH(J,2)  = THOUT
        RH(J)  = RHAMB
        XM(J)  = X12/(1.-X12)
        H(J,1)  = HJ2
        H(J,2)  = HJ2
  120 CONTINUE
      IF (PDE .EQ. 1.) GO TO 35
C MEIERING CAN AG ENG 19-49-77; GRUNDL 27-1-77.
      OTTEN = XM(IND1)
C WET SIDE USED TO RESET OTTEN
      DO 121  J = 1, IND1
        IF (XM(J) .GT. OTTEN) OTTEN = XM(J)
  121 CONTINUE
      RETURN
   35 CONTINUE
      XMT = X12/(1.-X12)
C XMT IS M USED, THT IS THETA USED , RHAMB IS RH USED XME
      XMC = XMT
      CALL DEPOT (8,D1,D2,D3,D4,D5)
      KVAD = 0
      JFLAG = 1
      F1 = DELX
      YL = 0.
      N = 0
      IF ( .NOT. REUSE) CALL DEPOT (11,F1,D2,D3,D4,D5)
   36 YL = YL + DELT
      N = N + 1
      XMT5 = XMC
      CALL DEPOT (7,RHAMB,THOUT,XMT5,XMC,D5)
      CALL DEPOT (10,D1,D2,D3,D4,XMC)
C PRINT AT EVERY 30-TH TIME USING MOD(N,30)
      IF (XY .EQ. 2. .AND. .NOT. REUSE .AND. MOD(N,30) .EQ. 0) PRINT 903
     1, YL
      IF (XY .EQ. 2. .AND. .NOT. REUSE .AND. MOD(N,30) .EQ. 0) CALL DEPO
     1T (11,F1,D2,D3,D4,D5)
      IF (YL .LT. TB) GO TO 36
      IF ( .NOT. REUSE) PRINT 903, YL
      IF ( .NOT. REUSE) CALL DEPOT (11,F1,D2,D3,D4,D5)
      CALL DEPOT (1,D1,D2,D3,D4,D5)
      RETURN
C
  901 FORMAT (1X,F10.2* PERCENT OF VOLUME ABOVE THRESHOLD OF *E10.4* F;
     1(AFFECTS *A10* )*)
  902 FORMAT (10X,F10.2* PERCENT FOR AT LEAST *E10.4* HRS** (*I1*/*I1* O
     1F PASSAGE TIME)*)
  903 FORMAT (1X,* TIME (HR) *E10.4)
  904 FORMAT (//,1X,F10.4* BU/HR-FT2 ;TEMPER FOR *F10.4* HR*)
  905 FORMAT (1X*STAGE=*I1,1H:,I1*  MAV FOR: SEGMENTS STAGE*3(1X,F10.4),
     1/,1X*LB-H2O/HR SEGMENTS,STAGE,CUMULATIVE*4(1X,F10.4),/,16X,*BTU/LB
     2-H2O THIS STAGE AND CUMULATIVE*2(1X,F10.1),/,16X,*KJ/KG-H2O THIS S
```

```
     3TAGE AND CUMULATIVE*2(1X,F10.1))
  906 FORMAT (//* AVERAGE AIR EXHAUST TEMP, F:*,13X,F12.4/* AVERAGE AIR
     1EXHAUST HUM.RATIO:*,10X,F12.4/* WATER REMOVED, LB/HR PER FT OF COL
     2UMN WIDTH*F12.4,/,* INLET MOISTURE EQUILIBRIUM, WB:*,10X,F12.4)
  907 FORMAT (* DRY AIR FLOW RATE, LB/HR-FT2:*10X,F12.2/* STATIC PRESSUR
     1E INCH H20:*,16X,F12.4,/,* HORSEPOWER PER FT COLUMN WIDTH FOR STAG
     2E  *F12.4,/,* HORSEPOWER PER FT COLUMN WIDTH CUMULATIVE *F12.4)
  908 FORMAT (/30X*AIR TEMPERATURE*/,1X*X=*F8.4,10F10.4)
  909 FORMAT (/30X*PRODUCT TEMPERATURES*/,1X*X=*F8.4,10F10.4)
  910 FORMAT (/30X*ABSOLUTE HUMIDITIES*/,1X*X=*F8.4,10F10.4)
  911 FORMAT (/30X*RELATIVE HUMIDITIES*/,1X*X=*F8.4,10F10.4)
  912 FORMAT (/30X*MOISTURE CONTENTS*/,1X*X=*F8.4,10F10.4)
  913 FORMAT (11(F10.4))
  914 FORMAT (1X*FUEL BURNED ENERGY USED BY THIS STAGE BTU/HR** PER FT C
     1OLUMN WIDTH *G10.4,/,3X*THETA(OUTLET) SEGMENTS STAGE*,4X,3(1X,F10.
     22))
      END
C*********************************************************************
      SUBROUTINE CRSPR(YL,XMAVE,THAVE,RHK,XMEINW)
C IPS X-PRINTOUT OF RESULTS AT SELECTED Y-LAYER FROM CRSFLWJ
C*****
      LOGICAL VERIFY,REPNT,REUSE
      COMMON/MEIER/OTTEN,OM,OFLAG
      COMMON/HOPT/ REPNT,HI3,HI4,TI3,TI4,REUSE,TINE,HINE,VERIFY,FHIN,ATI
     1N,FATIN
      COMMON/ARRAYS/XM(100),RH(100),T(100,2),H(100,2),TH(100,2),GA
      COMMON/MAIN/XMT,THT,RHT,DELT,CFM,XMO,KAB
      COMMON/BROOK/TOTEN,TOTH2O,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBTPR,XWIDE,PDE
      COMMON/VEL/FL,FL1,KK2,XREL,KSTG,THZIN,VREL
      COMMON/CYCLE/XMOUT,SUMZT,HAVER,THOUT,BTUH2O
      COMMON//XY,IADJ,IXY,SXMD,ADJ(6,1)
C*****
      IF (YL .GT. GVEL*DELT) GO TO 2
      IF (XY .EQ. 0.) GO TO 1
      DO 101  I = 2, IND1
        ADJ(1,I+IADJ) = ADJ(1,I-1+IADJ) + DELX
  101 CONTINUE
    1 CONTINUE
      OM = XM(1)
      IF (IPROD .EQ. 1) XMEIN = EMC(RH(1),TH(1,1))
      I = -1
      IF (IPROD .EQ. 2) XMEIN = SOYEMC(RH(1),TH(1,1))
      XMEINW = XMEIN/(1.+XMEIN)
      IF (FL1 .EQ. 1.) KSIDE = KSTG
      IF (FL1 .EQ. 0.) KSIDE = 9999
      IF ( .NOT. REUSE) PRINT 901, NSTG, KSIDE
    2 CONTINUE
      IF (XY .EQ. 0.) GO TO 3
      I = I + 1
      DO 102  J = 1, IND1
```

```
      ADJ(2,J+IND1*I+IADJ) = TH(J,2)
      ADJ(3,J+IND1*I+IADJ) = T(J,2)
      ADJ(4,J+IND1*I+IADJ) = XM(J)
      ADJ(5,J+IND1*I+IADJ) = H(J,2)
      ADJ(6,J+IND1*I+IADJ) = RH(J)
  102 CONTINUE
    3 CONTINUE
      TIME = YL/GVEL
C NOW O=SUM=SUMRH=SUMT=SUMTH SO THAT AVERAGE IS BETWEEN MIN-MAX
C BEFORE THESE = XM(1)=RH(1)=T(1,1)=TH(1,1)
      SUM = 0.
      XMIN = XM(1)
      XMAX = XMIN
      TMIN = T(2,1)
      TMAX = TMIN
      THMIN = TH(2,1)
      SUMRH = 0.
      THMAX = THMIN
      SUMT = 0.
      SUMTH = 0.
      DO 103  J = 2, IND1
        IF (XM(J) .GT. XMAX) XMAX = XM(J)
        IF (XM(J) .LT. XMIN) XMIN = XM(J)
        IF (T(J,1) .GE. TMAX) TMAX = T(J,1)
        IF (T(J,1) .LE. TMIN) TMIN = T(J,1)
        IF (TH(J,1) .GE. THMAX) THMAX = TH(J,1)
        IF (TH(J,1) .LE. THMIN) THMIN = TH(J,1)
        SUMT = SUMT + T(J,1)
        SUMRH = SUMRH + RH(J)
        SUMTH = SUMTH + TH(J,1)
        SUM = SUM + XM(J)
  103 CONTINUE
      XMAVE = SUM/FLOAT(IND1-1)
      TAVE = SUMT/FLOAT(IND1-1)
C BEFORE PRINTED TAVE INSTEAD OF TOUT
      THAVE = SUMTH/FLOAT(IND1-1)
      RHAVG = SUMRH/FLOAT(IND1-1)
      IF (FL .EQ. 0.) THZIN = THMAX
      IF (FL .EQ. 1.) THZIN = AMAX1(THZIN,THMAX)
      XMWB = XMAVE/(1.+XMAVE)
      XMINW = XMIN/(1.+XMIN)
      XMAXW = XMAX/(1.+XMAX)
      OM = XM(IND1)
      IF (IPROD .EQ. 1) XMEOUT = EMC(RH(IND1),TH(IND1,1))
      IF (IPROD .EQ. 2) XMEOUT = SOYEMC(RH(IND1),TH(IND1,1))
      XMEOUTW = XMEOUT/(1.+XMEOUT)
      DELXM = (XM(IND1)/(1.+XM(IND1))) - (XM(1)/(1.+XM(1)))
      IF ( .NOT. REUSE) PRINT 902, TIME, YL, XMINW, XMWB, XMAXW, THMIN,
     1THAVE, THMAX, H(IND1,1), RHK, XMEOUTW, T(IND1), DELXM
      RETURN
C
```

```
  901 FORMAT (///*  TIME=DEPTH*4X*MOISTURE-WB*6X*TEMPERATURE*6X*STAGE=*I
     12* SIDE=*I2,/,3X*HR    FT    XMIN    MAVE   XMAX   THMIN THAVE THMAX**
     2 HOUT RHOUT MEOUT TOUT M(OUT-IN)*)
  902 FORMAT (2X,F4.2,F6.2,F6.4,2F6.4,3F6.1,F6.4,F6.2,F6.4,F6.1,F6.4)
      END
C**********************************************************************
      SUBROUTINE DATA(IPROD)
C*****        SUBROUTINE USED FOR INITIALIZING CONSTANTS FOR PRODUCTS
      COMMON/PRPRTY/ SA,CA,CV,CW,RHOP,CP
      COMMON/HLATENT/HA,HB,HFG
C CHTC SET IN XFLO : MODEL/VALUES SEE BAKKER 1974 AES224.
C RO=RADIUS IS SET IN DEPOT
C REFT SET IN CRSFLWJ.
      IF (IPROD .EQ. 2) GO TO 1
C*****        INITIALIZE CONSTANTS FOR CORN
      SA = 239.
      CA = 0.242
      CV = 0.45
      CW = 1.0
      RHOP = 38.71
      HA = 4.349
      HB = -28.25
      CP = 0.268
      RETURN
C*****        INTIALIZE CONSTANTS FOR SOYBEANS
    1 SA = 464.3
      CA = 0.242
      CV = 0.45
      CW = 1.0
      RHOP = 57.99
      HA = 0.21624
      HB = -6.233
C IPS NOTE CP FOR SOYBEAN IS MOISTURE DEPENDENT (DEFINED ELSEWHERE)
C IPS CP IS USED 1) T3 CRSFLW1, 2)CON1 SOLVE, 3)CCON5 SOLVE4.
      RETURN
      END
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE DEPOT(ITFNL,RHAVG,THAVE,XMAVG,XMC,XTEM)
C MAX DIMENSIONED FOR IDE=7 WHERE N=IDE
C SUB-DEPOT CONTROLS PDE FOR M: INITIALIZATION; ITERATIVE UNSET
C SOLUTION WHEN CALLED BY SOLVE-SOLVE4; RESET SOLUTIN WHEN
C CALLED BY CRSFLWJ; AVERAGE BETWEEN STAGES WHEN CALLED BY XFLO OR
C CURRENT TEMPER MODEL IN CRSFLWJ.
      COMMON/MEIER/OTTEN,OM,OFLAG
      COMMON/EMCOP/IDE,IDEPOT,RADIUS,XME,DIFF,TEMPCO,MC,MRCB,RESET
      DIMENSION O(10)
      COMMON/LSM/ZKNT
      LOGICAL PDE2,DEBUG, ZKNT
      COMMON/CNARRAY/CN(10)
      DIMENSION CONE(9),VAD(10,20)
      EXTERNAL EMCPDE
```

```
      REAL MC,MRCB
      LOGICAL TEMPCO,RESET
      COMMON/IFLAGS/JFLAG,ICON,THIGH,KVAD,JUAN,APR23
      COMMON/MAIN/XMT,THT,RHT,DELT,CFM,XMO,KAB
      COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBTPR,XWIDE,PDE
      COMMON/BROOK/TOTEN,TOTH2O,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      COMMON/NAMES/MDOT(4,3)
      DATA (MDOT(I,3),I=1,4)/10H(M) BY PDE, 10H(D) SABBAH, 10HSOYS :CORN
     1, 10HALAM:DEBOR/
      DATA NVAD/20/
      G(U) = (U-32.)/1.8
      DEBUG = .FALSE.
      IF (DEBUG) PRINT 901, ITFNL, KVAD, JFLAG, RHAVG, THAVE, XMAVG, XMC
     1, XTEM
      IDE = 7
      N = IDE
      IDEPOT = ITFNL
      DT = DELT
      NP1 = N + 1
      NP2 = N + 2
      NP3 = N + 3
C *NUMBERS* ARE ITFNL POINTER IN COMPUTED GO TO STATEMENT.
      GO TO (7,7,3,3,6,1,1,3,1,2,8), ITFNL
C *6*7*9* DRY-TEMPER-RESET
    1 DO 101  I = 1, NP1
C  SET INTERNAL MOISTURE FOR EMCPDE =CN(I)
         CN(I) = VAD(I,KVAD+JFLAG)
  101 CONTINUE
C SET TOTAL MOISTURE (M) FOR EMCPDE = MRCB
      MRCB = VAD(NP2,KVAD+JFLAG)
      IF (ITFNL .EQ. 6 .OR. ITFNL .EQ. 9) TEMPCO = .FALSE.
      IF (ITFNL .EQ. 7) TEMPCO = .TRUE.
C RADIUS CORN = 0.19 INCH BAKKER 1971 TASAE VOL 15 PP 864 TABLE.
      IF (IPROD .EQ. 1) RADIUS = 0.00488
      IF (IPROD .EQ. 2) RADIUS = 0.00457
C SET OM AND COMPUTE XME (FOR CONVERGENCE XME=1 WHEN CONDENSATION)
      OM = XMAVG
      IF (IPROD .EQ. 1) XME = EMC(RHAVG,THAVE)
      IF (IPROD .EQ. 2) XME = SOYEMC(RHAVG,THAVE)
      IF (ICON .NE. 0) XME = 1.
C CORN PDE=2 ABOVE 160 CHU:HUSTRULID 1968 TASAE VOL 11 P705 EQ21
C WITH XM GIVEN DECIMAL INSTEAD PERCENT, AND 6.8 INCLUDING 0.045*273.
      IF (IPROD .EQ. 1 .AND. PDE2 .AND. THAVE .GT. 160.) DIFF = 1.513E -
     1 4*EXP((0.045*G(THAVE)+6.806)*XMAVG-2513./(G(THAVE)+273.13))
C CORN PDE=1  SABBAH 1972 TRANS ASAE VOL 15 PP763 EQ7.
C CORN SABBAH (D=FT2/HR BEFORE 3.28) D=M2/HR ,M=DEC. T=F.
      IF (IPROD .EQ. 1 .AND. .NOT. PDE2) DIFF = 0.057*XMAVG*EXP(-4812./(
     1THAVE+460.))/((3.28)*(3.28))
C CORN PDE=2 BELOW 160  SABBAH 1972 TRANS ASAE VOL 15 PP763EQ7.
      IF (IPROD .EQ. 1 .AND. PDE2 .AND. THAVE .LE. 160.) DIFF = 0.057*XM
     1AVG*EXP(-4812./(THAVE+460.))/((3.28)*(3.28))
```

```
C SOYBEAN DALPASQUALE FORM OF SABBAH EQUATION
      IF (IPROD .EQ. 2) DIFF = 0.0469437*EXP(-3437.16/(G(THAVE)+273.13))
C HYBRID DRYING FACTOR (READ IN XFLO) USED TO ADJUST DIFF(USIVITY)
      DIFF = HDF*DIFF
C RESET PERMITS MULTIPLE CALLS TO EMCPDE BY ZEROIN.
      RESET = .TRUE.
      IF (ITFNL .EQ. 9) MC = XTEM
      ZKNT = .FALSE.
C BRANCHES TO EMCPDE TO SOLVE DIFFUSION EQUATION FOR SPHERE
      AVG = EMCPDE(DT)
      IF (DEBUG) PRINT 902, MC, DT
      IF (ITFNL .NE. 9) AVG = 0.
      DELTA = 0.0003
      IF (ITFNL .EQ. 9 .AND. DEBUG) PRINT 902, AVG, DELTA
C M-PDE RESET TO M-EQ13MSUAES224 ONLY WHEN LOCKSTEP ERROR GREATER DELTA
      IF (ITFNL .EQ. 9 .AND. ABS(AVG) .LE. DELTA) GO TO 2
C UNRESET SOUGHT TOTAL MOISTURE IS = XMC
      IF (ITFNL .NE. 9) XMC = MC
      IF (ITFNL .EQ. 6 .OR. ITFNL .EQ. 7) RETURN
C **9** RETURN IF TEMPORARY ESTIMATE, ELSE RESET X-TRACK
      MC = XTEM
      TLOW = AMIN1(-3.*DELT,45000.*DELT*(MRCB-XTEM))
      EPS = 0.0001
      IF (RHAVG .GT. 0.98) EPS = 0.00001
      THI = AMAX1(3.*DELT,5000.*DELT*(MRCB-XTEM))
      IF (DEBUG) PRINT 903, MRCB, XTEM, TLOW, THI
      ZKNT = .TRUE.
      CALL ZEROIN4 (TLOW,THI,EPS,EMCPDE)
C ZKNT WHEN ZEROIN4 FAILS TO CONVERGE ; HENCE ACCEPT CURRENT VALUES
C FOR VAD STORED IN EMCPDE. CALL EMCPDE AND RETRIEVE THESE VALUES.
      IF (ZKNT) AVG = EMCPDE(DT)
      IF (ZKNT) XTEM = VAD(NP2,KVAD+JFLAG)
      IF (DEBUG) PRINT 904, ZKNT, TLOW, AVG
      ZKNT = .FALSE.
C STORE RESET  INTERNAL M EITHER WITHIN DELTA OR ZEROIN4 LOCKSTEP
    2 DO 102  I = 1, NP1
        VAD(I,KVAD+JFLAG) = CN(I)
  102 CONTINUE
      VAD(NP2,KVAD+JFLAG) = XTEM
C SET NP3 THE X-POSITION IS WITHIN DRYER FLAG.
      VAD(NP3,KVAD+JFLAG) = 1.
      RETURN
C *3*4*8* INVERT OR AVERAGE INTERNAL MOISTURE
C SCAN X-POSITION TO DETERMINE WHETHER NP3 IS WITHIN DRYER
    3 DO 103  J = 1, NVAD
        NN = J - 1
        IF (VAD(NP3,J) .NE. 1.) GO TO 4
  103 CONTINUE
    4 CONTINUE
      IF (ITFNL .EQ. 8) GO TO 5
C *3*4* REVERSE VAD  AS CONVERT DOES FOR VARIABLES IN COMMON/ARRAYS/.
```

```
      IT = NN + 1
      IN = NN/2
      DO 107  I = 1, IN
        IT = IT - 1
        DO 104  J = 1, NP3
          O(J) = VAD(J,IT)
  104   CONTINUE
        DO 105  J = 1, NP3
          VAD(J,IT) = VAD(J,I)
  105   CONTINUE
        DO 106  J = 1, NP3
          VAD(J,I) = O(J)
  106   CONTINUE
  107 CONTINUE
C *3* RETURN IF MERELY ANALOGOUS TO CALL TO CONVERT; REVERSE VAD ARRAYS.
      IF (ITFNL .EQ. 3) RETURN
    5 CONTINUE
C *4* AVERAGE EACH SIDE OF OTTEN INVERTER
      IF (ITFNL .EQ. 4) KK = 2
C *8* AVERAGE AS SINGLE SIDE WHEN EITHER MIX BETWEEN STAGES
C OR CURRENT UNIFORM TEMPER MODEL IN CRSFLWJ.
      IF (ITFNL .EQ. 8) KK = 1
      DO 111  K = 1, KK
        IF (KK .EQ. 1) JM = 1
        IF (KK .EQ. 1) JP = NN
        IF (KK .EQ. 2 .AND. K .EQ. 1) JM = 1
        IF (KK .EQ. 2 .AND. K .EQ. 1) JP = KVAD
        IF (KK .EQ. 2 .AND. K .EQ. 2) JM = MINO(NN,KVAD+1)
        IF (KK .EQ. 2 .AND. K .EQ. 2) JP = NN
        DO 110  I = 1, NP2
          AVG = 0.
          DO 108  J = JM, JP
            AVG = AVG + VAD(I,J)
  108     CONTINUE
          AVG = AVG/FLOAT(JP-JM+1)
          DO 109  J = JM, JP
            VAD(I,J) = AVG
  109     CONTINUE
  110   CONTINUE
  111 CONTINUE
      DO 112  I = 2, NP2
        CONE(I) = (FLOAT(I-1)**3-FLOAT(I-2)**3)/FLOAT(NP1**3)
  112 CONTINUE
      DO 115  K = 1, KK
        IF (KK .EQ. 2 .AND. K .EQ. 1) JM = 1
        IF (KK .EQ. 2 .AND. K .EQ. 1) JP = KVAD
        IF (KK .EQ. 2 .AND. K .EQ. 2) JM = MINO(NN,KVAD+1)
        IF (KK .EQ. 2 .AND. K .EQ. 2) JP = NN
        MC = 0.
        DO 113  I = 1, NP1
          IF (K .EQ. 1) JK = 1
```

```
            IF  (K .EQ. 2)  JK = NN
            MC = MC + CONE(I+1)*VAD(I,JK)
  113     CONTINUE
          DO 114  J = JM, JP
            VAD(NP2,J)  = MC
  114     CONTINUE
  115 CONTINUE
      RETURN
C **5** INITIALIZE FOR X-TRACK INLET CONDITIONS
    6 DO 117  J = 1, NVAD
        DO 116  I = 1, NP2
          VAD(I,J)  = XMAVG
  116   CONTINUE
        VAD(NP3,J)  = O.
  117 CONTINUE
C SET FLAG (PDE2) FOR SAY TWO TEMPERATURE REGION DIFF(USIVITY).
      PDE2 = .FALSE.
      IF  (PDE .EQ. 2.) PDE2 = .TRUE.
      IF  (PDE .EQ. 2.) PDE = 1.
      RETURN
C *1*2* RESETS VAD AFTER TEMPERS (IF LOSS MOISTURE) (NOTE *2 NOT CALL)
C NOTE CURRENT TEMPER MODEL IN CRSFLWJ IS NON X-DEPENDENT USE VAD(NP2,1)
    7 DO 118  J = 1, NVAD
        VAD(NP2,J)  = VAD(NP2,1)
  118 CONTINUE
      DO 120  J = 1, NVAD
        DO 119  I = 1, NP1
          VAD(I,J)  = VAD(I,1)
  119   CONTINUE
  120 CONTINUE
      RETURN
C **11** PRINTOUT OF INTERNAL MOISTUE (M) WHEN XY=2.
    8 F6 = RHAVG*FLOAT(KVAD) - RHAVG
      I = JFLAG
      PRINT 905, F6 + I*RHAVG,VAD(NP2,KVAD+I)/(1.+VAD(NP2,KVAD+I))
     1     ,NP1,(VAD(J,KVAD+I)/(1.+VAD(J,KVAD+I)),J=1,NP1)
C
  901 FORMAT (6H DEPOT,3I2,5(1X,E10.4))
  902 FORMAT (6H DEPOT,2(1X,E10.4))
  903 FORMAT (6H DEPOT,4(1X,E10.4))
  904 FORMAT (6H DEPOT,L2,2(1X,E10.4))
  905 FORMAT (1X*X= *F8.4* ; MC= *F8.4* INTERNAL*I2* NODES =*,/,8(1X,F9.
     13))
      END
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      FUNCTION EMCPDE(DT)
C SUB-EMCPDE DIFFUSION EQUATION FOR SPHERE (METHOD OF LINES) WITH
C BC EITHER XME OR INSULATED(TEMPERING)
C MAX DIMENSIONED FOR IDE=7 WHERE NP1=IDE+1
      COMMON/EMCOP/IDE,IDEPOT,RADIUS,XME,DIFF,TEMPCO,MC,MRCB,RESET
      COMMON/LSM/ZKNT
```

```
      LOGICAL DEBUG, ZKNT
      COMMON/CNARRAY/CN(10)
C ***** DT TIME INTERVAL (DELT)
C ***** RADIUS RADIUS OF SPHERE
C ***** XME, BOUNDARY CONDITION COMPUTED USING EMC OR SOYEMC
C ***** DIFF DIFFUSION COEFFICIENT
C ***** TEMPCO, BOUNDARY CONDITION FLAG F)M=XME, T)M IS INSULATED  .
C ***** MC, MOISTURE VARIABLE IN PDE GIVEN IN MSU AES RR 224.
C ***** CN, ARRAY NOW CN(5) FOR MOISTURE AT EACH INTERNAL NODE
      DIMENSION AI(8,8),B(8,8),C(8),CONA(9),CONE(9),CONB(9),D(8)
      DIMENSION DY(8),CND(8),Y(8)
      INTEGER STEP
      LOGICAL TEMPCO,RESET
      REAL MC,MRCB,MCJS
      DATA B, AI, C, CONA, CONB/154*0./
      DEBUG = .FALSE.
      NODE = IDE
      NP1 = NODE + 1
      NP2 = NODE + 2
C WHEN RESET=FALSE EMCPDE  BEING CALLED BY ZEROIN; ELSE CALLED BY DEPOT
      DO 101  I = 1, NP1
        IF (RESET) CND(I) = CN(I)
        IF ( .NOT. RESET) CN(I) = CND(I)
  101 CONTINUE
      RESET = .FALSE.
C ZKNT: ACCEPT CURRRENT VALUES STORED IN CND WHEN ZEROIN4 FAILS TO
C CONVERGE WHEN ZEROIN4 IS CALLED BY DEPOT.
      IF (ZKNT) RETURN
      STEP = 1
      LAYER = NP1
      IF (LAYER .LT. 1) LAYER = 1
      IF (LAYER .GT. NP1) LAYER = NP1
C LAYER IS NUMBER OF OUTER LAYERS IN VOLUME AVERAGE
      FN = FLOAT((NP1**3)-((NP1-LAYER)**3))
      DO 102  J = 1, NP1
        AI(J,J) = 1.
  102 CONTINUE
      DELR = RADIUS/FLOAT(NP1)
C PASSAGE TIME DT AND INTEGRATION TIME DTINT ARE USUALLY SAME (STEP=1)
      DTINT = DT/FLOAT(STEP)
      CON1 = DIFF/(DELR*DELR)
      DO 103  IN = 2, NP2
        CONA(IN) = FLOAT(IN)/FLOAT(IN-1)
        CONE(IN) = (FLOAT(IN-1)**3-FLOAT(IN-2)**3)/FN
        CONB(IN) = FLOAT(IN-2)/FLOAT(IN-1)
  103 CONTINUE
      B(1,1) = -6.*CON1
      B(1,2) = 6.*CON1
      DO 104  J = 2, NODE
        B(J,J-1) = CON1*CONB(J)
        B(J,J) = -2.*CON1
```

```
         B(J,J+1) = CON1*CONA(J)
  104 CONTINUE
      IF (TEMPCO) GO TO 1
C SET COEFFICIENTS FOR DRYING
      C(NP1) = CON1*CONA(NP1)*XME
      B(NP1,NP1) = -2.*CON1
      B(NP1,NODE) = CONB(NP1)*CON1
      AI(NP1,NODE) = 0.
      AI(NP1,NP1) = 1.
      GO TO 2
    1 CONTINUE
C SET COEFFICIENTS FOR TEMPERING
      C(NP1) = CON1*CONB(NODE)*CN(NODE)
C     B(NP1,NP1)=-8.*CON1/3.
C     B(NP1,NODE)=8.*CONB(NP1)*CON1/3.
      AI(NP1,NP1) = 1.
C     AI(NP1,NODE)=-CONB(NP1)/3.
      B(NP1,NP1) = -2.*CON1
      B(NP1,NODE) = CON1*CONB(NP1)
C SYMMETRIC MODEL OR STEFFE MODEL FOR TEMPERING
    2 CONTINUE
      OLD = 0.
      DO 105  I = 1, LAYER
        IN = NP2 - I
        OLD = OLD + CN(IN)*CONE(IN+1)
  105 CONTINUE
C SOLVE THE ODE  ( A  DY/DT = B Y +  C  )  BY EULER'S METHOD
      DO 106  I = 1, NP1
        DY(I) = 0.
  106 CONTINUE
      DO 113  IDT = 1, STEP
        DO 108  I = 1, NP1
          SUM = 0.
          JM = I - 1
          JM = MAX0(JM,1)
          JP = I + 1
          JP = MIN0(NP1,JP)
          DO 107  J = JM, JP
            SUM = SUM + B(I,J)*CN(J)
  107     CONTINUE
C USE Y AS STORAGE FOR (BY + C) IN EULER'S METHOD
          Y(I) = SUM + C(I)
  108   CONTINUE
        DO 110  I = 1, NP1
          SUM = 0.
          JM = I
          IF (TEMPCO .AND. I .EQ. NP1) JM = I - 1
          JP = I
          DO 109  J = JM, JP
            SUM = SUM + AI(I,J)*Y(J)
  109     CONTINUE
```

```
           D(I) = SUM
  110   CONTINUE
        DO 111  I = 1, NP1
          DY(I) = DY(I) + D(I)
          Y(I) = CN(I) + DTINT*D(I)
  111   CONTINUE
C SET CN TO THE COMPUTED MOISTURE VALUES
        DO 112  I = 1, NP1
C THE MINIMUM VALUE OF CN IS ZERO; ELSE FAILURE TO CONVERGE ZEROIN4.
          IF (DT .GE. 0.) CN(I) = AMAX1(0.,Y(I))
          IF (DT .LT. 0.) CN(I) = AMAX1(0.,Y(I))
  112   CONTINUE
  113 CONTINUE
      MCJS = 0.
      DO 114  I = 1, LAYER
        IN = NP2 - I
        MCJS = MCJS + CN(IN)*CONE(IN+1)
  114 CONTINUE
      MCJS = MRCB + (MCJS-OLD)
      MCJS = AMAX1(MCJS,0.)
      DO 115  I = 1, NP1
        DY(I) = DY(I)/FLOAT(STEP)
  115 CONTINUE
C *6*7*9* DRY-TEMPER-RESET (*9*EMCPDE IS COST FUNCTION FOR ZEROIN4)
      IF (IDEPOT .EQ. 6) MC = MCJS
      IF (IDEPOT .EQ. 7) MC = MCJS
      IF (IDEPOT .EQ. 9) EMCPDE = MC - MCJS
      RETURN
      END
C**********************************************************************
           FUNCTION HEATLAT(XMC,TH)
C*****
C*****     FUNCTION USED FOR COMPUTING THE LATENT HEAT OF VAPORIZATION
C*****OF WATER IN THE GRAIN.
C FUNCTIONAL FORM GALLAHER 1951 AG ENG PP54 USED BY SPENCER
C J1972 J AGRIC ENGNG RES VOL 17 PP 189.
C*****
      COMMON/HLATENT/HA,HB,HFG
      HEATLAT = (1094.-0.57*TH)*(1.+HA*EXP(HB*XMC))
      IF (HEATLAT .LE. 1000.) HEATLAT = 1000.
      RETURN
C
      END
C**********************************************************************
      SUBROUTINE LAYEQ
C IPS USED BY CRSFLW, CRSFLW3, CRSFLW4;EQN5+6+7 IN MSUAESRR224.
C*****   DESCRIPTION
C*****         SUBROUTINE TO FIND THE MOISTURE CONTENT BASED ON EQUA-
C*****   TIONS BY J.M. TROEGER AND P.M. DEL GIUDICE
C LISTED IN BAKKER 1974 AES224 AS EQ7 FROM ASAE PAPER70-324 BY TROEGER
C THIS CODE IS A COMPOSITE OF LAYEQ BY TROEGER AND LAYEQ BY
```

```
C THOMPSON BOTH ON PP 49 RR 244.
C*****
C*****   USAGE
C*****         USED IN THE FIXED BED AND CROSSFLOW MODELS WITH GRAIN
C*****   TEMPERATURES BETWEEN 80 F AND 160 F
C*****
      COMMON/NAMES/MDOT(4,3)
      COMMON/MAIN/XMC,THT,RH,DELT,CFM,XMO,KAB
      COMMON/BROOK/TOTEN,TOTH2O,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      DATA (MDOT(I,1),I=1,4)/10HTROE+THOMP, 10H(M)BYLAYER, 10HCORN=MAIZE
     1, 10HDEBR+THOMP/
      P1(XM,R,T) = EXP(-2.45+6.42*XM**1.25-3.15*R+9.62*XM*SQRT(R)+.03*T-
     1.002*CFM)
      P2(R,T) = EXP(2.82+7.49*(R+.01)**.67-.0179*T)
      P3(P,Q) = -(.12*(XMO-XME))**(Q+1.)*P*Q
      Q1(XM,R,T) = -3.98 + 2.87*XM - (.019/(R+.015)) + .016*T
      Q2(R) = -EXP(.81-3.11*R)
      TF(P,Q,XO,XF,TO) = P*(XF-XME)**Q - P*(XO-XME)**Q + TO
      XMN(P,Q,XO,TI,TO) = ((TI-TO)/P+(XO-XME)**Q)**(1./Q) + XME
C*****   CALL READYTH FOR PRELIMINARY CHECKS AND CALCULATIONS
      IF (HDF .GE. 0.99 .AND. HDF .LE. 1.) HDRY = HDF
C SEE) BAKKER LEREW BROOK BROOKER ASAE 78-3523 CRS 0.99 BATCH 0.998
      IF (HDF .LT. 0.99 .OR. HDF .GT. 1.) HDRY = 1.
      CALL READYTH (TXMO,DELM,XME,IOOPS,XMR)
C*****   CHECK ABSORPTION FLAG...IF SET GO TO ABSORPTION SIMULATION
      IF (IOOPS-1) 1, 6, 1
    1 IF (THT .GT. 140.) GO TO 7
C*****   COMPUTE TRANSITION M,P1,Q1, AND FIRST TRANSITION TIME
      X1M = .4*DELM + XME
      X2M = .12*DELM + XME
      TINC = DELT*60.
      P = P1(TXMO,RH,THT)
      Q = Q1(TXMO,RH,THT)
      TX = TF(P,Q,TXMO,X1M,0.0)
C*****   CHECK IF PRESENT M IS IN FIRST REGION...IF IS IS COMPUTE
C*****   EQUIVALENT TIME AND ADD TINC
      IF (XMC .LT. X1M) GO TO 3
      TI = TF(P,Q,TXMO,XMC,0.0) + TINC
C*****   CHECK IF EQUIVALENT TIME+TINC IS LESS THAN TRANSITION TIME..
C*****   IF IT IS COMPUTE NEW M AND RETURN
      IF (TI .GT. TX) GO TO 2
      XMC = HDRY*XMN(P,Q,TXMO,TI,0.0)
      RETURN
C*****   EQUIVALENT TIME+TINC IS IN SECOND REGION--COMPUTE P2, Q2 AND
C*****   NEW M THEN RETURN
    2 P = P2(RH,THT)
      Q = Q2(RH)
      XMC = HDRY*XMN(P,Q,X1M,TI,TX)
      RETURN
C*****   M IS NOT IN.FIRST REGION--COMPUTE P2, Q2 AND SECOND
C*****   TRANSITION TIME
```

```
    3 P = P2(RH,THT)
      Q = Q2(RH)
      TX1 = TX
      TX = TF(P,Q,X1M,X2M,TX1)
C*****   CHECK IF PRESENT M IS IN SECOND REGION...IF IT IS COMPUTE
C*****   EQUIVALENT TIME AND ADD TINC
      IF (XMC .LT. X2M) GO TO 5
      TI = TF(P,Q,X1M,XMC,TX1) + TINC
C*****   CHECK IF EQUIVALENT TIME+TINC IS LESS THAN TRANSITION TIME..
C*****   IF IT IS COMPUTE M AND RETURN
      IF (TI .GT. TX) GO TO 4
      XMC = HDRY*XMN(P,Q,X1M,TI,TX1)
      RETURN
C*****   EQUIVALENT TIME+TINC IS IN THIRD REGION--COMPUTE P3, Q3 AND
C*****   NEW M THEN RETURN
    4 P = P3(P,Q)
      Q = -1.0
      XMC = HDRY*XMN(P,Q,X2M,TI,TX)
      RETURN
C*****   M IS NOT IN SECND REGION--COMPUTE P3, Q3, EQUIVALENT TIME+
C*****   TINC AND NEW M THEN RETURN
    5 P = P3(P,Q)
      Q = -1.0
      TI = TF(P,Q,X2M,XMC,TX) + TINC
      XMC = HDRY*XMN(P,Q,X2M,TI,TX)
      RETURN
C*****
C*****   ABSORPTION SIMULATION
C*****   FIND NEW M AND INCREMENT COUNTER (KAB)
    6 DIV = -.625*PSDB(THT+459.69)**(.466*RH)*RH*RH*RH
      XMC = HDRY*((XMC-XME)*EXP(DIV*DELT)+XME)
      KAB = KAB + 1
      RETURN
    7 ALMR = ALOG(XMR)
      A = -1.86178 + 0.0048843*THT
      B = 427.364*EXP(-0.03301*THT)
C****  FIND EQUIVALENT TIME BASED ON CURRENT TEMP AND MC
C****  ADD DELT AND SOLVE FOR NEW MC
      TI = ALMR*(A+B*ALMR) + DELT
      ALMR = (-A-SQRT(A*A+4.0*B*TI))/(2.0*B)
      XMC = HDRY*(DELM*EXP(ALMR)+XME)
      RETURN
      END
C***********************************************************************
      SUBROUTINE  LAYEQSO
C IPS USED BY CRSFLW,CRSFLW3,CRSFLW4.
C*****                V.A.DALPASQUALE
C*****DESCRIPTION
C*****     SUBROUTINE USED TO FIND THE MOISTURE CONTENT BASED ON
C*****EQUATION BY OVERHULTZ AND EQULIBRIUM MOISTURE CONTENT BY ROA
C CN FIG1 AND CK FIG2 OVERHULTS 1973 TASAE VOL 16 PP 112.
```

```
C*****
      COMMON/NAMES/MDOT(4,3)
      COMMON/MAIN/XMC,THT,RH,DELT,CFM,XMO,KAB
      COMMON/BROOK/TOTEN,TOTH20,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      DATA (MDOT(I,2),I=1,4)/10HOVERHULTZ., 10H(M)BYLAYER, 10HSOYBEAN...
     1, 10HSILVA+ALAM/
      F(T) = T + 459.69
      IF (HDF .GE. 0.99 .AND. HDF .LE. 1.) HDRY = HDF
C SEE) BAKKER LEREW BROOK BROOKER ASAE 78-3523 CRS 0.99 BATCH 0.998
      IF (HDF .LT. 0.99 .OR. HDF .GT. 1.) HDRY = 1.
C*****
C*****     CALL SOYREAD FOR PRELIMINARY CHECKS AND CALCULATIONS
      CALL SOYREAD (TXMO,DELM,XME,IOOPS,XMR)
      IF (IOOPS .EQ. 1) GO TO 6
      XMOW = XMO/(1.+XMO)
      IF (XMOW .LE. 0.20) GO TO 1
      IF (XMOW .GT. 0.20) GO TO 2
    1 CK = EXP(11.752-7912.7/F(THT))
      GO TO 4
    2 IF (XMOW .GT. 0.25) GO TO 3
      CK = EXP(10.906-7357.0/F(THT))
      GO TO 4
    3 CK = EXP(10.375-6779.3/F(THT))
    4 CN = 0.3529 + 0.00136*THT
      IF (CK .LE. 0.0) CK = 0.0001
      IF (TXMO .EQ. XMC) GO TO 5
      TI = (-ALOG(XMR))**(1./CN)/CK + DELT
      XMC = HDRY*((XMO-XME)*EXP(-((CK*TI)**CN))+XME)
      RETURN
    5 XMC = HDRY*((XMO-XME)*EXP(-((CK*DELT)**CN))+XME)
      RETURN
    6 DIV = -.625*PSDB(F(THT))**(.466*RH)*RH*RH*RH
      XMC = HDRY*((XMC-XME)*EXP(DIV*DELT)+XME)
      KAB = KAB + 1
      RETURN
      END
C*************************************************************************
      FUNCTION OPTH(HLS)
C OPTH IS CALLED BY ZEROIN TO FIND LOCKSTEP HUMIDITY WHEN AIR IS
C RECYCLED IN SUBROUTINE ABSH.
C SAME AS XFLO BETWEEN C-----  EXCEPT PRINTS DELETED
       COMMON/MEIER/OTTEN,OM,OFLAG
      COMMON/MAIN/XMT,THT,RHT,DELT,CFM,XMO,KAB
      COMMON/BROOK/TOTEN,TOTH20,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBTPR,XWIDE,PDE
      COMMON/PRPRTY/SA,CA,CV,CW,RHOP,CP
      COMMON/HLATENT/HA,HB,HFG
      COMMON/IFLAGS/JFLAG,ICON,THIGH,KVAD,JUAN,APR23
      COMMON /PRESS/PATM
      COMMON/NAMES/MDOT(4,3)
      COMMON/VEL/FL,FL1,KK2,XREL,KSTG,THZIN,VREL
```

```
      COMMON/CYCLE/XMOUT,SUMZT,HAVER,THOUT,BTUH2O
      COMMON/ARRAYS/XM(100),RH(100),T(100,2),H(100,2),TH(100,2),GA
      COMMON//XY,IADJ,IXY,SXMD,ADJ(6,1)
      LOGICAL REUSE,REPNT,VERIFY
      COMMON/HOPT/ REPNT,HI3,HI4,TI3,TI4,REUSE,TINE,HINE,VERIFY,FHIN,ATI
     1N,FATIN
      DATA TRN/0.001/, REPNT/.FALSE./, VERIFY/.FALSE./
      F(T) = T + 459.69
      REWIND 5
      VERIFY = .FALSE.
C ----- MODIFY REWIND 5 INSTEAD OF REUSE FALSE ----
      KAB = 0
      DELX = 0.1
      DELT = 0.002
      THZIN = 0.
      THIGH = 0.0
      YADD = 0.
      NSTG = 1
      KSTG = 1
      TOTEN = 0.
      TOTH2O = 0.
      FL = 0.0
      READ 907, STAGES
      READ 907, EQN
      READ 907, PDE
      IF (PDE .LT. 0.) PDE = 0.
      IF (PDE .NE. 0.) PDE = 1.
      READ 907, PRODUCT
    1 CONTINUE
      KVAD = 0
      READ 907, XWIDE
      IF (NSTG .EQ. 1) XVAD = XWIDE
      IF (NSTG .GE. 2 .AND. PDE .NE. 0.) XWIDE = XVAD
      XWIDE = XWIDE/12.
      READ 907, YLENG
      READ 907, DBTPR
      READ 907, XY
      IF (PDE .EQ. 0. .AND. XY .EQ. 2.) XY = 1.
      IF (XY .NE. 1. .AND. XY .NE. 2.) XY = 0.
      READ 907, BPH
      READ 907, TB
      GVEL = BPH*1.244
      TRY1 = 5.
      IADJ = 4 + INT(YLENG/(DELT*GVEL*TRY1*DBTPR))
      YADD = YLENG/FLOAT(IADJ-4)
      IF (XY .EQ. 0.) CALL SETFL (ADJ(6,IADJ))
      GP = GVEL*RHOP
      KO = KN
      KN = 1 + INT((XWIDE+TRN)/DELX)
      UL1 = FL1
      IF (NSTG .GE. 2) CALL UNMIX1 (KO,KN,KO1,KO2,UL1)
```

```
READ 907, FM
IF (NSTG .EQ. 1) READ 907, HDF
IF (HDF .EQ. 0.) HDF = 1.
READ 907, THIN
IF (THIN .EQ. 0.) THIN = THOUT
IF (NSTG .GE. 2) XMO = 100.*XMS/(1.+XMS)
READ 907, XMOW
IF (XMOW .EQ. 0.) XMOW = XMO
XMO = XMOW/(100.-XMOW)
XMS = XMO
IF (NSTG .EQ. 1) OTTEN = XMO
IF (NSTG .EQ. 1) READ 907, TAMB
IF (NSTG .EQ. 1) READ 907, RHAMB
IF (RHAMB .GT. 1.) RHAMB = RHAMB/(10**(1+INT(ALOG10(RHAMB))))
TY = RHAMB
XMT5 = XMO
IF (NSTG .EQ. 1 .AND. PDE .EQ. 1.) CALL DEPOT (5,D1,D2,XMT5,D4,D5)
READ 907, TIN
IF (TIN .EQ. 1. .AND. NSTG .GE. 2) TINE = TAMB
IF (TIN .EQ. 0.) TIN = TIN1
IF (TIN .EQ. 1.) TIN = TAMB
IF (TIN .EQ. 2.) TIN = SUMZT
THIGH = AMAX1(THIN,TIN,THZIN)
IF (NSTG .EQ. 1) TIN1 = TIN
IF (NSTG .EQ. 1) READ 907, FUEL
IF (FUEL .LT. 0.) REUSE = .TRUE.
IOP3 = 2
IOP4 = 3
HI = HADBRH(F(TAMB),RHAMB)
IF (NSTG .EQ. 1) HI3 = HLS
IF (NSTG .EQ. 1) CALL ABSH (HIN,TAMB,TIN,HI,FUEL)
IF (NSTG .EQ. 1) GTINE = TINE
IF (NSTG .EQ. 1) FHIN = HIN
IF (NSTG .EQ. 1) HIN1 = HIN
IF (NSTG .GE. 2) READ 907, HIN
IF (HIN .EQ. 1. .AND. NSTG .GE. 2) HINE = HI
IF (HIN .EQ. 0.) HIN = HIN1
IF (HIN .EQ. 1.) HIN = HI
IF (HIN .EQ. 2.) HIN = HAVER
READ 907, CFMBU
CFM = CFMBU*XWIDE/1.244
FL = 0.
READ 907, FL1
IF (FL1 .EQ. 0.) XREL = 1.
IF (FL1 .EQ. 0.) VREL = 1.
IF (FL1 .EQ. 0.0) GO TO 3
READ 907, XREL
XWIDE1 = XWIDE*XREL
XWIDE2 = XWIDE - XWIDE1
IND1 = INT((XWIDE1+TRN)/DELX) + 1
KO1 = IND1
```

```
      GO TO 4
    2 FL = 1.
      KSTG = 2
      READ 907, VREL
      IND1 = INT((XWIDE2+TRN)/DELX) + 1
      KO2 = IND1
      GVEL = GVEL*VREL
      CALL UNMIX2 (KO,KN,KO1,KO2,UL1)
      IF (XY .NE. 0.) ADJ(1,1+IADJ) = XWIDE1
      GO TO 7
    3 IND1 = INT((XWIDE+TRN)/DELX) + 1
    4 RHIN = RHDBHA(F(TIN),HIN)
      RHT = AMAX1(0.,AMIN1(1.,RHIN))
C SET AIR INLET VALUES THAT DO NOT DEPEND ON UNMIX.
      DO 101  I = 1, IND1
        H(I,2) = HIN
        H(I,1) = HIN
        RH(I) = RHT
  101 CONTINUE
      IF (NSTG .GE. 2) READ 907, RTYPE
      IF (NSTG .EQ. 1) RTYPE = 1.
      ITYPE = INT(RTYPE)
      IF (NSTG .GE. 2) READ 907, UNMIX
      IF (NSTG .EQ. 1) UNMIX = 2.
      IF (NSTG .GE. 2 .AND. UNMIX .NE. 1.) UNMIX = 2.
C SET AIR INLET SIDE (DUAL) OR ALL TOP (SINGLE SPEED);AFTER IND1SET
      IF (UNMIX .EQ. 1.) GO TO 5
      DO 102  I = 1, IND1
        T(I,2) = THIN
        T(I,1) = T(I,2)
  102 CONTINUE
    5 CONTINUE
      IF (UNMIX .EQ. 2. .AND. RTYPE .EQ. 2. .AND. NSTG .GE. 2) CALL UNMI
     1X3 (KO,KN,KO1,KO2,UL1)
      IF (NSTG .GE. 2) CALL UNMIX1 (KO,KN,KO1,KO2,UL1)
      IF (UNMIX .EQ. 2. .AND. NSTG .GE. 2 .AND. PDE .EQ. 1. .AND. RTYPE
     1.EQ. 1.) CALL DEPOT (8,D1,D2,D3,D4,D5)
      IF (UNMIX .EQ. 2. .AND. NSTG .GE. 2 .AND. PDE .EQ. 1. .AND. RTYPE
     1.EQ. 2.) CALL DEPOT (4,D1,D2,D3,D4,D5)
      IF (UNMIX .EQ. 1. .AND. NSTG .GE. 2 .AND. PDE .EQ. 1. .AND. RTYPE
     1.EQ. 2.) CALL DEPOT (3,D1,D2,D3,D4,D5)
      IF (UNMIX .EQ. 1.) GO TO 6
C SET VALUES WHEN MIXED (INCLUDES TOP OF FIRST STAGE)
      DO 103  I = 1, IND1
        XM(I) = XMO
        IF (EQN .EQ. 1. .OR. EQN .EQ. 2.) TH(I,2) = T(I,2) = T(I,1) = TH
     1  IN
        IF (EQN .EQ. 3. .OR. EQN .EQ. 4.) TH(I,2) = THIN
        TH(I,1) = TH(I,2)
  103 CONTINUE
    6 CONTINUE
```

```
      IXY = 1 + INT(YLENG/DBTPR)
      IF (XY .NE. 0.) CALL SETFL (ADJ(6,IADJ+IXY*IND1))
      IF (XY .NE. 0.) ADJ(1,1+IADJ) = 0.
      UL1 = FL1
      IF (ITYPE .EQ. 2) CALL CONVERT (KO,KN,KO1,KO2,UL1)
C SET NODE AT AIR INLET AFETER MIXING/AIRREVERSAL
      TH(1,2) = TIN
      TH(1,1) = TH(1,2)
      T(1,2) = TH(1,1)
      T(1,1) = T(1,2)
      GA = 60.*CFM/VSDBHA(F(TINE),HINE)
      CHTC = 0.363*(GA**0.59)
      IF (GA .LT. 500.) CHTC = 0.69*(GA**0.49)
    7 IF (XY .EQ. 0.) KADJ = IADJ
      IF (XY .NE. 0.) KADJ = IADJ + IXY*IND1
      CALL CRSFLWJ (TIN,THIN,HIN,YADD,TAMB,EQN)
      KVAD = IND1 - 1
      IF (FL1 .EQ. 0.) FL = 1.
      IF (FL .EQ. 0.) GO TO 2
      IF ((NSTG .EQ. IOP3)) HI3 = HAVER
      IF (NSTG .EQ. IOP4) FHI4 = HI4
      IF ((NSTG .EQ. IOP4)) HI4 = HAVER
      IF (NSTG .EQ. IOP3) FTI3 = TI3
      IF ((NSTG .EQ. IOP3)) TI3 = SUMZT
      IF (NSTG .EQ. IOP4) FTI4 = TI4
      IF ((NSTG .EQ. IOP4)) TI4 = SUMZT
      IF (NSTG .GE. STAGES .AND. FL .EQ. 1.) GO TO 8
      KSTG = 1
      NSTG = NSTG + 1
      GO TO 1
C ------------ MODIFY BY EXTRA PRINTOUT ---------
    8 OPTH = (HLS-HI3)*(HLS-HI3)
      PRINT 906, HLS, HI3
      PRINT 903, FTI3, TI3
      PRINT 902, FHI4, HI4
      PRINT 904, FTI4, TI4
      VERIFY = .TRUE.
      CALL ABSH (HIN,TAMB,TIN,HI,FUEL)
      VERIFY = .FALSE.
      PRINT 901, GTINE, ATIN
      PRINT 905, FHIN, HIN
C
  901 FORMAT (1X*TAG ALONG: T TO BURNER*2(1X,E10.4))
  902 FORMAT (1X*TAG ALONG: COOLER HUMIDITY*2(1X,E10.4))
  903 FORMAT (1X*TAG ALONG: RECYCLE TEMPERATURE*2(1X,E10.4))
  904 FORMAT (1X*TAG ALONG: COOLER TEMPERATURE*2(1X,E10.4))
  905 FORMAT (1X*TAG ALONG: H FROM BURNER*2(1X,E10.4))
  906 FORMAT (1X*LOCKSTEP  HUMIDITY  ASSUMED:ACTUAL*2(1X,E10.4))
  907 FORMAT (5F10.2)
      END
C*****************************************************************
```

```
      SUBROUTINE REFALSI(HLOW,HHI,EPS,FUNCT,XNP1)
C IPS USED BY CRSFLW3=CRSFWJ
C***** SUBROUTINE FINDS ZERO OF FUNCT ON (HLOW,HHI) BY FALSE POSITION
      DIMENSION FLOW(25),FHIGH(25),FN(25),HACT(25)
      KK = 1
      FN(1) = 0.
    1 FXL = FUNCT(HLOW)
      FLOW(KK+1) = FXL
      IF (FXL .LT. 0.) GO TO 2
      HLOW = HLOW*3./4.
      GO TO 1
    2 FXR = FUNCT(HHI)
      FHIGH(KK+1) = FXR
      IF (FXR .GT. 0.) GO TO 3
      HHI = HHI*4./3.
      GO TO 2
    3 TEST = FXL*FXR
      IF (TEST .GT. 0.) PRINT 901, FXL, FXR
      GO TO 6
    4 FXL = FXNP1
      FLOW(KK+1) = FXL
      GO TO 6
    5 FXR = FXNP1
      FHIGH(KK+1) = FXR
    6 XNP1 = (HLOW*FXR-HHI*FXL)/(FXR-FXL)
      HACT(KK+1) = XNP1
      IF (KK .GT. 25) GO TO 8
      FXNP1 = FUNCT(XNP1)
      FN(KK+1) = FXNP1
      KK = KK + 1
      IF (ABS(FN(KK)-FN(KK-1)) .LT. EPS) RETURN
      IF (FXL*FXNP1 .LT. 0.) GO TO 7
      HLOW = XNP1
      GO TO 4
    7 HHI = XNP1
      GO TO 5
    8 PRINT 903
      PRINT 902
      DO 101  J = 1, KK
        PRINT 904, J, FLOW(J), FHIGH(J), FN(J), HACT(J)
  101 CONTINUE
      RETURN
C
  901 FORMAT (10X,*W A R N I N G : POSSIBLY NO ROOTS*//* THE FUNCTION VA
     1LUE AT LOWER GUESS IS:*,E15.8/* THE FUNCTION VALUE AT HIGHER GUESS
     2 IS*,E15.8//)
  902 FORMAT (13X,5HF-LOW,13X,6HF-HIGH,9X,5HF-MID,9X,5HX-MID)
  903 FORMAT (10X,*NO ROOTS FOUND AFTER 50 ITERATIONS*)
  904 FORMAT (1X,I3,2X,E15.8,3X,E15.8,3X,E15.8,3X,E15.8)
      END
C*********************************************************************
```

```
      FUNCTION SOLVE(HJ2)
C IPS USED BY CRSFLW3 AND REFALSI TO COMPUTE XM=XMT, TH=THT, RH=RHT
C IPS SOLVE IS ZERO WHEN (EQN14-MSUAESRR224) IS SATISFIED AND
C IPS AND WHEN SOLVE IS ZERO H IS FOUND; ENGLISH UNITS
C IPS EQUATIONS DEVELOPED FOR LOW CFM SOLAR HENCE THETA(X,Y)
C IPS = T(X,Y) ASSUMPTION MADE SEE BAKKER,HAIGHT,ROTH ASAE76-3200.
C*****
C*****
      COMMON/ARRAYS/XM(100),RH(100),T(100,2),H(100,2),TH(100,2),GA
      COMMON/MAIN/XMT,THT,RHT,DELT,CFM,XMO,KAB
      COMMON/BROOK/TOTEN,TOTH2O,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      COMMON/PRPRTY/SA,CA,CV,CW,RHOP,CP
      COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBPTR,XWIDE,PDE
      COMMON/IFLAGS/JFLAG,ICON,THIGH,KVAD,JUAN,APR23
      COMMON/HLATENT/HA,HB,HFG
      COMMON/PRESS/PATM
      DATA PATM/14.696/, RHC/0.9998/, HMIN/0.001/
      F(T) = T + 459.69
      J = JFLAG
      JM = J - 1
      ICON = 0
C*****
C*****      EVALUATE THE CONSTANTS CON1....CON6 AND SET THE INITIAL
C***** GUESS FOR H
C IPS PERHAPS, ROTH BAKKER 1973 SIMULATION OF HEAT AND MASS TRANSFER
C IPS IN BEDS OF BIOLOGICAL PRODUCTS, AE812 SUMMER1973;USES 212 IN CON4
C*****
      H(J,2) = HJ2
C IPS BEFORE H(J,2) WAS RESET TO TENTH.
      IF (H(J,2) .GT. 1.) H(J,2) = 1.0
      IF (J .EQ. 2) GO TO 1
      CON55 = H(J,2) - H(JM,2)
      CON2 = DELT*GA*(CA+CV*H(JM,2))
      GO TO 2
    1 CON55 = H(2,2) - H(1,2)
      CON2 = DELT*GA*(CA+CV*H(1,2))
    2 CONTINUE
      IF (IPROD .EQ. 2) CP = 0.39123 + 0.46057*XM(J)
      CON1 = DELX*RHOP*(CP+CW*XM(J))
      CON3 = CW - CV
      CON4 = CON3*212. + HFG
      CON5 = DELT*GA*CON4
      CON6 = RHOP*DELX/(DELT*GA)
C ASSUME C3=0 WHICH CHANGES C4 BY UNDER 2 PERCENT: SUBSTITUTE
C BAKKER 1974 AES 224 RHS EQ 12 INTO RHS EQ 13  THEN LET THETA=T YIELDS
C (C1+C2)*T(J,2)=C1*T(J,1)+C2*T(JM,2)+C5*CON55 WHERE
C DT/DY=(T(J,2)-T(J,1))/DY AND DT/DX=(T(J,2)-T(JM,2))/DX.
C NOTE SECOND TERM EQ13 HAS WRONG OPPOSITE SIGN,HENCE SIGN CON55 TERM .
      T(J,2) = (CON1*T(J,1)+CON2*T(JM,2)-CON5*CON55)/(CON1+CON2-DELT*GA*
     1CON3*CON55)
      IF (T(J,2) .LT. 32.1) GO TO 3
```

```
C*****
C*****     COMPUTE RH AND CHECK FOR CONDENSATION
C*****
      IF (H(J,2) .LE. 0.) H(J,2) = APR23
      RH(J) = RHDBHA(F(T(J,2)),H(J,2))
      IF (RH(J) .GE. RHC) GO TO 4
C*****
C*****     FIND XM ACCORDING TO THE THIN-LAYER DRYING EQUATION.
C*****
      XMT = XM(J)
      IF (T(J,2) .GT. THIGH) T(J,2) = THIGH
      THT = T(J,2)
      RHT = AMAX1(0.,AMIN1(1.,RH(J)))
      IF (PDE .NE. 1. .AND. IPROD .EQ. 1) CALL LAYEQ
      IF (PDE .NE. 1. .AND. IPROD .EQ. 2) CALL LAYEQSO
      RHT5 = RHT
      THT5 = THT
      XMT5 = XMT
      IF (PDE .EQ. 1.) CALL DEPOT (6,RHT5,THT5,XMT5,XMC,D5)
      IF (PDE .EQ. 1.) XMT = XMC
    3 CONTINUE
      IF (T(J,2) .LT. 32.1) T(J,2) = 32.1
C*****
C*****     SOLVE SHOULD CONVERGE TO ZERO UPON INTERATION IN ZEROIN.
C*****
      SOLVE = XMT - XM(J) + (HJ2-H(JM,2))/CON6
C*****
C ACTUAL(AESRR224:EQ14) MOISTURE CONTENT IS XMT:SOLVE4 ONLY NEAR ZERO
C*****
C IPS EQN-14 MSUAESRR224 DM/DY=(GA/GP)DH/DX
      XMT = XM(J) - (H(J,2)-H(JM,2))/CON6
      RETURN
C*****
C*****     CONDENSATION SIMULATOR
C*****
C*****     CALCULATE THE WET-BULB TEMPERATURE OF THE PREVIOUS POINT.
C***** THIS IS THE DESIRED DRY-BULB TEMPERATURE AT THE SATURATION
C***** POINT.
C*****
    4 GSLOW = T(JM,2)/3.
      T(J,2) = -459.69 + WBDBHAS(F(T(JM,2)),H(JM,2),F(GSLOW),F(THIGH),0.
     101)
      TH(J,2) = T(J,2)
      H(J,2) = HADBRH(F(T(J,2)),RHC)
      RH(J) = RHC
      ICON = 1
      GO TO 3
      END
C***************************************************************************
      FUNCTION SOLVE4(HJ2)
C IPS SOLVE4 USED BY BOTH ZEROIN4 AND CRSFLW4;SIGN 2ND TERM EQN13 PLUS!
```

```
      COMMON/ARRAYS/XM(100),RH(100),T(100,2),H(100,2),TH(100,2),GA
      COMMON/MAIN/XMT,THT,RHT,DELT,CFM,XMO,KAB
      COMMON/BROOK/TOTEN,TOTH2O,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      COMMON/PRPRTY/SA,CA,CV,CW,RHOP,CP
      COMMON/INPT/BPH,GP,GVEL,IND1,DELX,YLENG,DBPTR,XWIDE,PDE
      COMMON/IFLAGS/JFLAG,ICON,THIGH,KVAD,JUAN,APR23
      COMMON/HLATENT/HA,HB,HFG
      COMMON/PRESS/PATM
      DATA PATM/14.696/, RHC/0.9998/, HMIN/0.001/
      F(T) = T + 459.69
      J = JFLAG
      JM = J - 1
      ICON = 0
C*****
C*****     EVALUATE THE CONSTANTS CON1....CON6 AND SET THE INITIAL
C***** GUESS FOR H.
C*****
C     HJ2=AMIN1(1.,AMAX1(0.,HJ2))
      H(J,2) = HJ2
      CCON1 = GA*(CA+CV*H(J,2))
C IPS CCON1  H(J,2) INSTEAD OF AVG. AS MSUAES-63.
      CCON2 = DELX*CHTC*SA
      CCON3 =  (CCON2-GA*CV*(H(J,2)-H(JM,2)))*DELT
C UNLIKE MSUAESRR224+EQN13 CCON3 HAS MINUS GA INSTEAD OF PLUS GA.
      CCON4 = DELT*HFG*GA*(H(J,2)-H(JM,2))
      IF (IPROD .EQ. 2) CP = 0.39123 + 0.46057*XM(J)
      CCON5 = DELX*RHOP*(CP+CW*XM(J))
      CCON6 = GA*DELT/(RHOP*DELX)
      T(J,2) =  (CCON1*T(JM,2)+CCON2*TH(J,2))/(CCON1+CCON2)
C T(J,2) FROM (TJ2-TJM2)C1=C2(THJ2-TJ2) FIND TJ2 AS MSUAES+12
      TH(J,2) =  (CCON3*T(J,2)-CCON4+CCON5*TH(J,1))/(CCON5+CCON3)
C UNLIKE MSUAESRR224+EQN13 CCON4 HAS MINUS INSTEAD OF PLUS
C TH(J,2) FROM (THJ2-THJ1)C5=C3(TJ2-THJ2)-C4 FIND THJ2 AS MSUAES+EQN13.
C*****
C*****     COMPUTE RH AND CHECK FOR CONDENSATION
C*****
      IF (H(J,2) .LE. 0.) H(J,2) = APR23
      RH(J) = RHDBHA(F(T(J,2)),H(J,2))
      IF (RH(J) .GE. RHC) GO TO 2
C*****
C*****     FIND XM ACCORDING TO THE THIN-LAYER DRYING EQUATION;THT,RHT
C*****
      XMT = XM(J)
C RR224 USES THT=(TH(J,2)+T(J,2))/2.; THIS INCREASES DRYER EFFICIENCY
      THT = (TH(J,2)+T(J,2))/2.
      RHT = AMAX1(0.,AMIN1(1.,RH(J)))
      IF (PDE .NE. 1. .AND. IPROD .EQ. 1) CALL LAYEQ
      IF (PDE .NE. 1. .AND. IPROD .EQ. 2) CALL LAYEQSO
      RHT5 = RHT
      THT5 = THT
      XMT5 = XMT
```

```
      IF (PDE .EQ. 1.) CALL DEPOT (6,RHT5,THT5,XMT5,XMC,D5)
      IF (PDE .EQ. 1.) XMT = XMC
C*****
    1 CONTINUE
C IPS ESTIMATE OF H BY IMPLICIT ITERATION TILL SOLVE=ZERO.
C*****
      SOLVE4 = XMT - XM(J) + (HJ2-H(JM,2))*CCON6
C*****
C ACTUAL(AESRR224:EQ14) MOISTURE CONTENT IS XMT:SOLVE4 ONLY NEAR ZERO
      XMT = XM(J) - (H(J,2)-H(JM,2))*CCON6
      RETURN
C*****
C*****     CONDENSATION SIMULATOR
C*****
C*****     CALCULATE THE WET-BULB TEMPERATURE OF THE PREVIOUS POINT.
C***** THIS IS THE DESIRED DRY-BULB TEMPERATURE AT THE SATURATION
C***** POINT.
C*****
    2 T(J,2) = -459.69 + WBDBHAS(F(T(JM,2)),H(JM,2),F(32.1),F(THIGH),0.0
     11)
      H(J,2) = HADBRH(F(T(J,2)),RHC)
      CCON1 = GA*(CA+CV*H(J,2))
C IPS CCON1  H(J,2) INSTEAD OF AVG. AS MSUAES-63.
      CCON3 = (CCON2-GA*CV*(H(J,2)-H(JM,2)))*DELT
C UNLIKE MSUAESRR224+EQN13 CCON3 HAS MINUS GA INSTEAD OF PLUS GA.
      CCON4 = DELT*HFG*GA*(H(J,2)-H(JM,2))
      TH(J,2) = (CCON3*T(J,2)-CCON4+CCON5*TH(J,1))/(CCON5+CCON3)
C UNLIKE MSUAESRR224+EQN13 CCON4 HAS MINUS INSTEAD OF PLUS
      RH(J) = RHC
      ICON = 1
      GO TO 1
C
      END
C************************************************************************
      FUNCTION SOYEMC(RH,T)
      COMMON/MEIER/OTTEN,OM,OFLAG
C IPS USED BY SOYREAD,DEPOT,CRSPR,CRSFLWJ.
C*****
C*****     FUNCTION SUBROUTINE TO COMPUTE EQUILIBRIUM MOISTURE CONTENT
C*****OF SOYBEANS FROM A RELATIVE HUMIDITY AND TEMPERATURE,USING
C*****EQUATION BY SILVA
C SILVAXFLO (UP2182)USES HENDERSON-THOMPSON AND SABBAH.
C*****
      IF (T .LT. 32.) T = 33.
      IF (RH .LT. 0.55) GO TO 1
      T = 5./9.*(T-32.)
      RH = RH*100.
      SOYEMC = 6.20806*EXP(RH*0.027377)/ALOG(T)
      SOYEMC = SOYEMC/100.
      IF (OFLAG .EQ. 1.) SOYEMC = SOYEMC*((OM/OTTEN)**3)
      RH = RH/100.
```

```
      T = 9.*T/5. + 32.
      RETURN
    1 CONTINUE
      RH = RH*100.
      T = 5./9.*(T-32.)
      IF (RH .LT. 1.) RH = 1.
      SOYEMC = 3.96183*RH**0.49188/ALOG(T)
      SOYEMC = SOYEMC/100.
      IF (OFLAG .EQ. 1.) SOYEMC = SOYEMC*((OM/OTTEN)**3)
      T = 9.*T/5. + 32.
      RH = RH/100.
      RETURN
      END
C*************************************************************************
            SUBROUTINE SOYREAD(TXMO,DELM,XME,IOOPS,XMR)
      COMMON/MEIER/OTTEN,OM,OFLAG
C IPS USED BY LAYEQSO COMPARABLE TO READYTH=CORN USED BY LAYEQ.
C*****
C*****
C*****DESCRIPTION
C*****      SUBROUTINE TO MAKE PRELIMINARY CHECKS AND CALCULATIONS FOR
C*****SOYBEAN THINLAYER EQUATIONS AND TO CALCULATE EQUILIBRIUM MOISTURE
C*****CONTENT FOR SOYBEANS USING ALAMS EQUATION
C*****
      COMMON/MAIN/XMC,THT,RH,DELT,CFM,XMO,KAB
      COMMON/BROOK/TOTEN,TOTH2O,XMS,CHTC,UNMIX,TY,TB,IPROD,FM,HDF,NSTG
      OM = XMC
      IOOPS = 0
C*****COMPUTE EQUILIBRIUM MOISTURE CONTENT, COMPARE TO PRESENT MOISTURE
C*****CONTENT...IF GREATER SET IOOPS=1
      XME = SOYEMC(RH,THT)
      IF (XME-XMC) 2, 1, 1
    1 IOOPS = 1
C*****COMPARE PRESENT MOISTURE CONTENT TO INITIAL MOISTURE CONTENT. SET
C*****TXMO EQUAL TO THE LARGER VALUE
    2 IF (XMO-XMC) 3, 4, 4
    3 TXMO = XMC
      GO TO 5
    4 TXMO = XMO
C*****COMPUTE MOISTURE RATIO
    5 XMR = (XMC-XME)/(TXMO-XME)
      DELM = TXMO - XME
C IPS DELM NOT USED BUT CONSISTENT WITH READYTH;USED IN SUBROUTINE QUAL.
      RETURN
      END
C*************************************************************************
      SUBROUTINE SUB(KPT,Y,DEPNT,IV,IFLAG)
C CONCEPT BY MARK HARDING 1981; MODIFIED SLIGHTLY BY IP SCHISLER 1981.
C IPS USED BY CRSFLWJ TO INTERPOLATE ADJ-ARRAY; WHEN TWO GP IN CROSSFLOW
      COMMON//XY,IADJ,IXY,SXMD,ADJ(6,1)
      IF (IFLAG .EQ. 2) GO TO 1
```

```
C FIND ARRAY INDEX CORRESPONDING TO Y-POSITION
      KPTMAX = KPT
      DO 101  I = 1, KPT
        DEPNT = FLOAT(I)
        IF (Y .LT. ADJ(1,I)) RETURN
  101 CONTINUE
      RETURN
C DEPENDENT VARIABLE (DEPNT) IS BETWEEN ADJ(.,LPT) AND ADJ(.,LPT+1)
    1 LPT = KPT - 1
      LPT = MAX0(1,KPT)
      LPT = MIN0(LPT,KPTMAX-1)
      DEPNT = (((Y-ADJ(1,LPT))/(ADJ(1,LPT+1)-ADJ(1,LPT)))*(ADJ(IV,LPT+1)
     1-ADJ(IV,LPT))) + ADJ(IV,LPT)
      RETURN
      END
C*************************************************************************
      SUBROUTINE ZEROIN4(A,B,EPS,FUNC)
C IPS USED BY CRSFLW4,SEARCHES FOR DOMAIN CONTAINING ZERO AND FINDS ZERO
      COMMON/LSM/ZKNT
      LOGICAL ZKNT,ZPNT
      LOGICAL IPS
      REAL I,M
      IPS = .FALSE.
C ZPNT: PRINTS FAILURE TO CONVERGE UNLESS CALLED BY DEPOT.
      ZPNT = .TRUE.
      IF (ZKNT) ZPNT = .FALSE.
      IF (ZKNT) ZKNT = .FALSE.
      N = 1
      S1 = A
      S2 = B
    1 FA = FUNC(A)
      FB = FUNC(B)
      FC = FA
      C = A
      IF (IPS) GO TO 3
      IF (SIGN(1.,FB) .NE. SIGN(1.,FC)) GO TO 2
      S1 = A
      S2 = B
      N = N + 1
      IF (ZPNT .AND. N .GE. 25) PRINT 901, A, B, N
      IF (N .GE. 25) C = (A+B)/2.
      IF (N .GE. 25) A = C
      IF (N .GE. 25) B = C
C FAILURE TO CONVERGE TEST: FLAG IS ZKNT IN COMMON/LSM/.
      IF ( .NOT. ZPNT .AND. N .GE. 25) ZKNT = .TRUE.
      IF (N .GE. 25) RETURN
      IF (A .GE. 0.) A = A/2.
      IF (A .LT. 0.) A = 3.*A/2.
C IPS A AND B SET WIDER UNTIL FUNC CHANGES SIGN UNLIKE ZEROIN FIXED B-A.
      B = B*3./2.
      GO TO 1
```

```
    2 IPS = .TRUE.
      IF (A .EQ. S1 .AND. B .EQ. S2) GO TO 3
C IPS USE RESULTS OF SEARCH WHEN SET A AND B; BEFORE DID NOT.
      FS1 = SIGN(1.,FUNC(S1))
      FS2 = SIGN(1.,FUNC(S2))
      FA = SIGN(1.,FUNC(A))
      FB = SIGN(1.,FUNC(B))
      IF (FA .NE. FS1 .AND. FB .EQ. FS2) B = S1
      IF (FB .NE. FS2 .AND. FA .EQ. FS1) A = S2
      IF (FA .NE. FS1 .AND. FB .NE. FS2) B = S1
C IPS SELECT SMALLEST ROOT WHENEVER MULTIPLE ROOTS
      GO TO 1
    3 IF (ABS(FC) .GE. ABS(FB)) GO TO 4
      C = B
      B = A
      A = C
      FC = FB
      FB = FA
      FA = FC
    4 IF (ABS(C-B) .LE. 2.*EPS) GO TO 8
      I = (B-A)*FB/(FB-FA)
      J = LEGVAR(I)
      M = (C+B)/2.
      IF (J .NE. 0) GO TO 5
      I = -I + B
      CHINT = (B-I)*(M-I)
      IF (CHINT) 6, 6, 5
    5 I = M
    6 IF (ABS(B-I) .GE. EPS) GO TO 7
      I = SIGN(1.,(C-B))*EPS + B
    7 A = B
      B = I
      FA = FB
      FB = FUNC(B)
      IF (SIGN(1.,FB) .NE. SIGN(1.,FC)) GO TO 3
      C = A
      FC = FA
      GO TO 3
    8 A = (C+B)/2.
      FA = FUNC(A)
      IF (SIGN(1.,FA) .EQ. SIGN(1.,FB)) B = C
      RETURN
C
  901 FORMAT (1X*ZEROIN4 (A,B)*2(1X,E10.4)* NO ROOT*I5* EXPANSION TRIES*
     1)
      END
```

APPENDIX B

Standard Method for Determination of Breakage with Stein Breakage Testers

a. Clean a 350-g sample using standard dockage procedure. Do no hand-picking except to remove large pieces of foreign material not removed by dockage equipment.

b. Measure and record moisture content. If cultivars are to be compared, adjust them to a common moisture basis and measure them at the same temperature.For routine work involving a large number of samples, they can be placed either in open ice cream containers fitted with a bottom screen or in paper sacks and kept in a cabinet equipped with a blower at 30 C and 60% R.H. for 7-10 days (Miller et al. 1979). Samples in marketing channels need not be adjusted for moisture content because information on susceptibility to breakage under actual conditions is desired.

c. Subdivide sample with a Boerner divider.

d. Weigh three 100 +/- 0.1-g samples.

e. Pour each subsample into the Stein breakage tester and run for exactly 4 minutes.

f. Remove cup.

g. Place subsample on a Gamet shaker (Dean Gamet Mfg. Co., Minneapolis, Minn.) and remove dust and small pieces of corn with a round-hole (12/64-inch) grain-dockage sieve during a sieving time of 30 seconds (30 strokes).

h. Weigh coarse material remaining on the 12/64-inch sieve. Make no attempt to assess breakage other than by loss in weight. Kernels with cracks and large pieces of corn remaining on the sieve are regarded as whole grain.

i. Average results from three subsamples and report results as the percentage of sample passing through the round-hole, grain dockage sieve (breakage, %).

APPENDIX C

CONVERSION FACTORS

Unit Conversions	English or Metric	SI
Area	1 ft^2	$9.290 \times 10^{-2} m^2$
Convective Heat-Transfer Coefficient	1 BTU/h ft^2 °F	5.678 W/m^2 °C
Density	1 lb/ft^3	$1.602 \times 10 kg/m^2$
Energy	1 kcal 1 BTU	$4.187 \times 10^3 J$ $1.055 \times 10^3 J$
Enthalpy, specific	1 BTU/lb	$2.326 \times 10^3 J/kg$
Force	1 lbf	4.448 N
Heat Flux	1 kcal/h m^2 1 BTU/h ft^2	1.163 W/m^2 3.155 W/m^2
Heat Release Rate (mass)	1 BTU/h lb	$6.461 \times 10^{-1} W/kg$
Length	1 ft	$3.048 \times 10^{-1} m$
Mass	1 lb 1 tonne 1 ton	$4.536 \times 10^{-1} kg$ $1.000 \times 10^3 kg$ $1.016 \times 10^3 kg$
Power	1 BTU/h 1 hp	$2.931 \times 10^{-1} W$ $7.457 \times 10^2 W$
Pressure	1 standard atmosphere 1 bar 1 lbf/in^2 1 in water 1 mm Hg	$1.013 \times 10^5 N/m^2$ $1.000 \times 10^5 N/m^2$ $6.895 \times 10^3 N/m^2$ $2.491 \times 10^2 N/m^2$ $1.333 \times 10^2 N/m^2$
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)

Unit Conversions	English or Metric	SI
Velocity	1 ft/h	8.467×10^{-5} m/s
Viscosity, absolute (or dynamic)	1 lb/ft h	4.134×10^{-4} kg/m s
Viscosity, kinematic	1 ft^2/h	2.581×10^{-5} m^2/s
Volume	1 bu (volume)	3.523×10^{-2} m^3
	1 ft^3	2.832×10^{-2} m^3
	1 U.S. gal	3.785×10^{-3} m^3
Airflow	1 cfm	2.832×10^{-2} m^3/min
	1 cfm	4.719×10^{-4} m^3/sec
	1 cfm/ft^2	3.048×10^{-1} m/min
	1 cfm/ft^2	5.080×10^{-3} m/sec

APPENDIX D

Sample Run of the Blount 10-60

```
 OPTIONS EXPLAINED IF: ATTACH,HELP.XFLO.
 ATTACH,P,PAUXCYBER. LIBRARY.P. HELP.
    NO.OF STAGES(DRYER+COOLER),NOT TEMPER:  3.0000
    NUMBER OF EQUATIONS IN THE SYSTEM
    (1= 3 EQ.-EXPL; 2= 3 EQ.-IMPL
    3= 4 EQ.-IMPL; 4= 4 EQ.-IMPL(DEBUG):    1.0000
PDE THINLAYER; N=0 Y=1 SH=2 :               2.0000
TYPE OF PRODUCT(CORN=1 OR SOYBEAN=2):       1.0000

CROSSFLOW GRAIN DRYER SIMULATION
USING THE (M) BY PDE (D) SABBAH  EQUATION FOR SOYS :CORN
AND EMC BY ALAM:DEBOR


 INPUT FOR STAGE=    1
    COLUMN WIDTH, IN:                        14.0000
    COLUMN LENGTH, FT:                       12.0000
    OUTPUT INTERVAL; FT:                      1.0000
XY; N=0 Y=1, NODE=2, SCAN=3:                  0.0000
    GRAINFLOW (BU/HR/SQ FT):                 15.0000
RATIO VOL. TEMPER/VOL. INPUT;                 1.0000
    FINE MATERIALS,DECIMAL:                    .0300
    HYBRID FACTOR,DEC :                       1.0000
    INLET GRAIN TEMP, F:                     60.0000
    INLET MOISTURE, WET BASIS PERCENT:       25.5000
    INLET AMBIENT TEMP, F :                  60.0000
    AMBIENT REL HUM, DEC :                     .6000
    CALCULATED AMBIENT ABS HUM=                .0066
INLET  AIR TEMP. (SAY,FROM HEATER),F:       200.0000
    TYPE OF FUEL USED (1=NO.2 FUEL
    2=NAT.GAS, 3=L.P.GAS):                    3.0000
DOES DRYER RECYCLE AIR ? 1=Y 0=N:             1.0000
LENGTH STAGE AIR EXHAUSTED:
LENGTH STAGE AIR RECYCLED:
LENGTH STAGE GRAIN COOLED:
     .0091 TO SAY      .0157 H  FROM BURNER:
     60.00 TO SAY     110.16  T TO BURNER:
--------
ENERGY BALANCE BASED ON H AND T:
    .0227  110.1000
FRACTION TO BURNER : RECYCLED, COOLER, MAKEUP
                      .36       .09        .56
    AIRFLOW, CFM/BU (AT FAN INLET):          90.0000
IS THIS A TWO SPEED GRAIN FLOW STAGE?
          YES - 1.0     NO - 0.0:             1.0000
    FRACTIONAL WIDTH,(IN DEC OF 1ST SIDE)      .5000


PRELIMINARY CALCULATED VALUES

AIRFLOW, CFM/SQ FT                 84.4051
DRY AIRFLOW RATE, LB/HR-FT2       340.1440
INLET MC(DRY BASIS DECIMAL)          .3423
GRAIN FLOW RATE, BUSHELS/HR-FT2 15.0000
BU PER HR PER FT OF COLUMN WIDTH  8.7500
GRAIN FLOW RATE, FT/HR            18.6600
```

TIME=DEPTH		MOISTURE-WB			TEMPERATURE			STAGE= 1 SIDE= 1			
HR	FT	XMIN	MAVE	XMAX	THMIN	THAVE	THMAX	HOUT	RHOUT	MEOUT	TOUT
.00	.04	.2524	.2548	.2556	60.0	85.7	71.4	.0110	99.98	.2474	60.0
.05	1.01	.2178	.2507	.2621	91.3	130.6	162.0	.0324	99.99	.2279	91.3
.11	2.02	.2011	.2429	.2610	103.8	147.6	172.0	.0349	73.49	.1281	103.8
.16	3.02	.1898	.2351	.2578	121.9	157.7	179.8	.0341	42.83	.0826	121.9
.22	4.03	.1812	.2272	.2537	132.6	162.6	184.7	.0360	33.72	.0695	132.6
.27	5.00	.1745	.2205	.2496	138.2	167.0	187.8	.0345	27.98	.0610	138.2
.32	6.01	.1685	.2137	.2452	143.4	170.0	190.1	.0330	23.45	.0528	143.4
.38	7.02	.1633	.2070	.2409	146.4	172.3	191.7	.0340	22.44	.0502	146.4
.43	8.02	.1587	.2010	.2367	150.1	175.4	192.8	.0327	19.72	.0443	150.1
.48	9.03	.1546	.195[illegible]	.2326	153.4	177.5	193.7	.0342	18.97	.0418	153.4
.54	10.00	.1510	.1894	.2288	154.7	178.9	194.4	.0325	17.47	.0387	154.7
.59	11.01	.1476	.1841	.2249	158.5	181.2	195.0	.0314	15.44	.0336	158.5
.64	12.02	.1444	.1789	.2195	160.4	182.9	195.5	.0305	14.36	.0309	160.4

AVERAGE AIR EXHAUST TEMP, F:	133.6153
AVERAGE AIR EXHAUST HUM.RATIO:	.0328
WATER REMOVED, LB/HR PER FT OF COLUMN WIDTH	52.4075
INLET MOISTURE EQUILIBRIUM, WB:	.0053
VELOCITY 2ND-SIDE/1ST-SIDE(SAY DEC)	.5000

PRELIMINARY CALCULATED VALUES

AIRFLOW, CFM/SQ FT	84.4051
DRY AIRFLOW RATE, LB/HR-FT2	340.1440
INLET MC(DRY BASIS DECIMAL)	.3423
GRAIN FLOW RATE, BUSHELS/HR-FT2	7.5000
BU PER HR PER FT OF COLUMN WIDTH	4.3750
GRAIN FLOW RATE, FT/HR	9.3300

TIME=DEPTH		MOISTURE-WB			TEMPERATURE			STAGE= 1 SIDE= 2			
HR	FT	XMIN	MAVE	XMAX	THMIN	THAVE	THMAX	HOUT	RHOUT	MEOUT	TOUT
.00	.02	.2549	.2550	.2550	59.9	59.9	59.9	.0085	77.32	.1579	59.9
.11	1.01	.2595	.2611	.2625	80.9	87.5	91.0	.0229	99.98	.2345	80.9
.22	2.02	.2611	.2622	.2628	94.2	96.6	97.9	.0356	99.98	.2260	94.2
.32	3.00	.2571	.2604	.2627	96.9	106.1	113.1	.0374	96.43	.2084	96.9
.43	4.01	.2511	.2565	.2616	101.9	115.8	125.3	.0406	89.82	.1762	101.9
.54	5.00	.2447	.2515	.2579	108.2	122.7	131.8	.0396	72.88	.1248	108.2
.64	6.01	.2384	.2461	.2532	114.3	128.6	137.5	.0382	59.07	.1041	114.3
.75	7.02	.2323	.2407	.2484	120.2	133.3	141.3	.0391	51.07	.0916	120.2
.86	8.01	.2266	.2356	.2434	124.6	137.2	144.8	.0376	43.66	.0823	124.6
.97	9.01	.2209	.2304	.2385	129.1	141.4	148.9	.0389	39.85	.0769	129.1
1.07	10.00	.2156	.2255	.2336	133.4	144.2	150.5	.0369	33.89	.0694	133.4
1.18	11.01	.2105	.2207	.2288	136.4	147.3	154.0	.0357	30.36	.0645	136.4
1.29	12.02	.2055	.2157	.2241	140.3	150.7	157.0	.0347	26.66	.0585	140.3

```
AVERAGE AIR EXHAUST TEMP, F:                    111.6810
AVERAGE AIR EXHAUST HUM.RATIO:                    .0358
WATER REMOVED, LB/HR PER FT OF COLUMN WIDTH       14.1586
INLET MOISTURE EQUILIBRIUM, WB:                   .2475
DRY AIR FLOW RATE, LB/HR-FT2:                   340.14
STATIC PRESSURE INCH H20:                         2.2368
HORSEPOWER PER FT COLUMN WIDTH FOR STAGE           .7136
HORSEPOWER PER FT COLUMN WIDTH CUMULATIVE          .7136
STAGE=1:2  MAV FOR: SEGMENTS STAGE       .2157       .1789       .1916
LB-H2O/HR SEGMENTS,STAGE,CUMULATIVE    14.1586    52.4075    66.5661    66.5661
               BTU/LB-H2O THIS STAGE AND CUMULATIVE      1390.3     1390.3
               KJ/KG-H2O THIS STAGE AND CUMULATIVE      3233.9     3233.9
FUEL BURNED ENERGY USED BY THIS STAGE BTU/HR PER FT COLUMN WIDTH  .9255E+05
  THETA(OUTLET) SEGMENTS STAGE          150.72      182.85      172.14


   11.2500 BU/HR-FT2 ;TEMPER FOR      .8574 HR
X=   0.0000 ; MC=    .1932 INTERNAL 8 NODES =
     .253      .253      .252      .248      .241      .225      .192      .130
 TIME (HR)  .8580E+00
X=   0.0000 ; MC=    .1763 INTERNAL 8 NODES =
     .233      .231      .225      .216      .203      .186      .168      .148
 INPUT FOR STAGE=    2
    COLUMN WIDTH, IN:                           14.0000
    COLUMN LENGTH, FT:                           6.7000
    OUTPUT INTERVAL; FT:                         1.0000
XY; N=0 Y=1, NODE=2, SCAN=3:                     0.0000
    GRAINFLOW (BU/HR/SQ FT):                    15.0000
RATIO VOL. TEMPER/VOL. INPUT;                    0.0000
    FINE MATERIALS,DECIMAL:                       .0300
    HYBRID FACTOR,DEC :                          1.0000
    INLET GRAIN TEMP, F:
 .1721E+03
    INLET GRAIN TEMP, F:                       172.1430
    INLET MOISTURE, WET BASIS PERCENT:
 .1916E+02
    INLET MOISTURE, WET BASIS PERCENT:          19.1568
INLET  AIR TEMP. (SAY,FROM HEATER),F:
(TIN) EITHER HEATER OR AMBIENT
 .2000E+03  .6000E+02                          200.0000
(ABS.HUM.) EITHER HEATER OR AMBIENT
 .2270E-01  .6576E-02                             .0227
    AIRFLOW, CFM/BU (AT FAN INLET):             90.0000
IS THIS A TWO SPEED GRAIN FLOW STAGE?
           YES - 1.0     NO - 0.0:               1.0000
    FRACTIONAL WIDTH,(IN DEC OF 1ST SIDE)          .5000
ARRAY CONVERSION TO REVERSE AIRFLOW
(1=NO CHANGES 2=REVERSE AIRFLOW):                1.0000
ARRAY AVERAGE THE TOP OF STAGE GRAIN MOISTURE ?
1=NO CHANGE; 2= MAKE MOISTURE UNIFORM :          2.0000
```

PRELIMINARY CALCULATED VALUES

AIRFLOW, CFM/SQ FT	84.4051
DRY AIRFLOW RATE, LB/HR-FT2	340.1440
INLET MC(DRY BASIS DECIMAL)	.2370
GRAIN FLOW RATE, BUSHELS/HR-FT2	15.0000
BU PER HR PER FT OF COLUMN WIDTH	8.7500
GRAIN FLOW RATE, FT/HR	18.6600

TIME=	DEPTH	MOISTURE-WB			TEMPERATURE			STAGE= 2 SIDE= 1			
HR	FT	XMIN	MAVE	XMAX	THMIN	THAVE	THMAX	HOUT	RHOUT	MEOUT	TOUT
.00	.04	.1758	.1810	.1910	170.0	176.5	174.4	.4322	99.88	.1736	170.3
.05	1.01	.1672	.1778	.1895	140.5	164.4	185.8	.0274	19.78	.0471	143.2
.11	2.02	.1603	.1738	.1878	152.6	176.8	191.6	.0290	16.50	.0377	152.6
.16	3.02	.1547	.1693	.1850	163.7	182.3	193.2	.0295	12.85	.0269	163.7
.22	4.03	.1500	.1649	.1812	169.0	184.9	194.2	.0291	11.24	.0223	169.0
.27	5.00	.1460	.1610	.1774	172.1	186.6	195.0	.0287	10.30	.0197	172.1
.32	6.01	.1424	.1572	.1735	174.6	187.9	195.5	.0282	9.59	.0178	174.6
.36	6.72	.1400	.1547	.1709	176.1	188.6	195.9	.0280	9.18	.0167	176.1

AVERAGE AIR EXHAUST TEMP, F:	163.3246
AVERAGE AIR EXHAUST HUM.RATIO:	.0306
WATER REMOVED, LB/HR PER FT OF COLUMN WIDTH	22.7558
INLET MOISTURE EQUILIBRIUM, WB:	.0053
VELOCITY 2ND-SIDE/1ST-SIDE(SAY DEC)	.5000

PRELIMINARY CALCULATED VALUES

AIRFLOW, CFM/SQ FT	84.4051
DRY AIRFLOW RATE, LB/HR-FT2	340.1440
INLET MC(DRY BASIS DECIMAL)	.2370
GRAIN FLOW RATE, BUSHELS/HR-FT2	7.5000
BU PER HR PER FT OF COLUMN WIDTH	4.3750
GRAIN FLOW RATE, FT/HR	9.3300

TIME=	DEPTH	MOISTURE-WB			TEMPERATURE			STAGE= 2 SIDE= 2			
HR	FT	XMIN	MAVE	XMAX	THMIN	THAVE	THMAX	HOUT	RHOUT	MEOUT	TOUT
.00	.02	.1911	.1914	.1917	171.6	171.7	172.3	.4553	99.89	.1727	171.6
.11	1.01	.1855	.1864	.1888	145.3	149.4	155.0	.0296	15.91	.0357	155.0
.22	2.02	.1831	.1843	.1876	140.0	144.2	147.6	.0306	23.72	.0545	140.2
.32	3.00	.1812	.1819	.1852	144.3	154.0	159.9	.0316	22.09	.0504	144.3
.43	4.01	.1754	.1783	.1813	152.4	159.8	164.1	.0323	18.41	.0412	152.4
.54	5.00	.1695	.1743	.1774	155.6	162.8	167.8	.0322	16.94	.0374	155.6
.64	6.01	.1638	.1699	.1736	157.8	165.4	170.7	.0316	15.78	.0345	157.8
.72	6.72	.1600	.1667	.1713	158.9	167.1	172.4	.0315	15.32	.0332	158.9

```
AVERAGE AIR EXHAUST TEMP, F:                    152.4371
AVERAGE AIR EXHAUST HUM.RATIO:                    .0325
WATER REMOVED, LB/HR PER FT OF COLUMN WIDTH      7.7620
INLET MOISTURE EQUILIBRIUM, WB:                   .2290
DRY AIR FLOW RATE, LB/HR-FT2:                   340.14
STATIC PRESSURE INCH H2O:                         2.2368
HORSEPOWER PER FT COLUMN WIDTH FOR STAGE          .3984
HORSEPOWER PER FT COLUMN WIDTH CUMULATIVE        1.1120
STAGE=2:2  MAV FOR: SEGMENTS STAGE       .1667       .1547       .1587
LB-H2O/HR SEGMENTS,STAGE,C ULATIVE     7.7620    22.7558    30.5178    97.0839
               BTU/LB-H2O THIS STAGE AND CUMULATIVE     1693.2     1485.6
               KJ/KG-H2O THIS STAGE AND CUMULATIVE     3938.4     3455.4
FUEL BURNED ENERGY USED BY THIS STAGE BTU/HR PER FT COLUMN WIDTH  .5167E+05
  THETA(OUTLET) SEGMENTS STAGE         167.07     188.65     181.45
 INPUT FOR STAGE=    3
    COLUMN WIDTH, IN:                         14.0000
    COLUMN LENGTH, FT:                         1.6000
    OUTPUT INTERVAL; FT:                       1.0000
XY; N=0 Y=1, NODE=2, SCAN=3:                   0.0000
    GRAINFLOW (BU/HR/SQ FT):                  15.0000
RATIO VOL. TEMPER/VOL. INPUT;                  0.0000
    FINE MATERIALS,DECIMAL:                     .0300
    HYBRID FACTOR,DEC :                        1.0000
    INLET GRAIN TEMP, F:
 .1815E+03
    INLET GRAIN TEMP, F:                     181.4534
    INLET MOISTURE, WET BASIS PERCENT:
 .1587E+02
    INLET MOISTURE, WET BASIS PERCENT:        15.8729
INLET  AIR TEMP. (SAY,FROM HEATER),F:
(TIN) EITHER HEATER OR AMBIENT
 .2000E+03  .6000E+02                         60.0000
(ABS.HUM.) EITHER HEATER OR AMBIENT
 .2270E-01  .6576E-02                           .0066
    AIRFLOW, CFM/BU (AT FAN INLET):           90.0000
IS THIS A TWO SPEED GRAIN FLOW STAGE?
           YES - 1.0     NO - 0.0:             1.0000
    FRACTIONAL WIDTH,(IN DEC OF 1ST SIDE)       .5000
ARRAY CONVERSION TO REVERSE AIRFLOW
(1=NO CHANGES 2=REVERSE AIRFLOW):              1.0000
ARRAY AVERAGE THE TOP OF STAGE GRAIN MOISTURE ?
1=NO CHANGE; 2= MAKE MOISTURE UNIFORM :        1.0000
```

PRELIMINARY CALCULATED VALUES

AIRFLOW, CFM/SQ FT	84.4051
DRY AIRFLOW RATE, LB/HR-FT2	382.5031
INLET MC(DRY BASIS DECIMAL)	.1887
GRAIN FLOW RATE, BUSHELS/HR-FT2	15.0000
BU PER HR PER FT OF COLUMN WIDTH	8.7500
GRAIN FLOW RATE, FT/HR	18.6600

TIME=	DEPTH	MOISTURE-WB			TEMPERATURE			STAGE= 3 SIDE= 1			
HR	FT	XMIN	MAVE	XMAX	THMIN	THAVE	THMAX	HOUT	RHOUT	MEOUT	TOUT
.00	.04	.1400	.1546	.1709	159.0	145.8	168.8	.0304	14.82	.0322	159.0
.05	1.01	.1408	.1554	.1696	81.3	105.1	148.8	.0237	14.93	.0359	148.8
.09	1.60	.1413	.1572	.1692	81.3	90.6	122.1	.0231	29.30	.0687	122.1

AVERAGE AIR EXHAUST TEMP, F:	148.9719
AVERAGE AIR EXHAUST HUM.RATIO:	.0257
WATER REMOVED, LB/HR PER FT OF COLUMN WIDTH	.9184
INLET MOISTURE EQUILIBRIUM, WB:	.2475
VELOCITY 2ND-SIDE/1ST-SIDE(SAY DEC)	.5000

PRELIMINARY CALCULATED VALUES

AIRFLOW, CFM/SQ FT	84.4051
DRY AIRFLOW RATE, LB/HR-FT2	382.5031
INLET MC(DRY BASIS DECIMAL)	.1887
GRAIN FLOW RATE, BUSHELS/HR-FT2	7.5000
BU PER HR PER FT OF COLUMN WIDTH	4.3750
GRAIN FLOW RATE, FT/HR	9.3300

```
 TIME=DEPTH    MOISTURE-WB       TEMPERATURE       STAGE= 3 SIDE= 2
  HR    FT   XMIN   MAVE   XMAX  THMIN THAVE THMAX  HOUT RHOUT MEOUT TOUT
  .00   .02 .1600 .1667 .1712 158.9 158.9 158.9 .2158 81.91 .1156 158.9
  .11  1.01 .1582 .1650 .1696 145.2 150.5 154.3 .0251 17.33 .0419 145.2
  .17  1.60 .1573 .1639 .1692 130.0 137.3 147.0 .0241 15.93 .0385 147.0


AVERAGE AIR EXHAUST TEMP, F:                        146.9071
AVERAGE AIR EXHAUST HUM.RATIO:                         .0290
WATER REMOVED, LB/HR PER FT OF COLUMN WIDTH          -1.5614
INLET MOISTURE EQUILIBRIUM, WB:                        .0324
DRY AIR FLOW RATE, LB/HR-FT2:                       382.50
STATIC PRESSURE INCH H20:                             2.2368
HORSEPOWER PER FT COLUMN WIDTH FOR STAGE               .0951
HORSEPOWER PER FT COLUMN WIDTH CUMULATIVE             1.2071
STAGE=3:2  MAV FOR: SEGMENTS STAGE        .1639        .1572        .1594
LB-H20/HR SEGMENTS,STAGE,CUMULATIVE     -1.5614        .9184       -.6430     96.4409
               BTU/LB-H20 THIS STAGE AND CUMULATIVE          0.0      1495.5
               KJ/KG-H20 THIS STAGE AND CUMULATIVE           0.0      3478.4
FUEL BURNED ENERGY USED BY THIS STAGE BTU/HR PER FT COLUMN WIDTH 0.
  THETA(OUTLET) SEGMENTS STAGE          137.32        90.58       106.16
    THIS IS THE END OF CROSSFLOW
TAG ALONG T TO BURNER ASSUMED:ACTUAL   .1101E+03  .1006E+03
TAG ALONG H FROM BURNER ASSUMED:ACTUAL   .2270E-01  .1964E-01
     STOP
     037300    FINAL EXECUTION FL.
      7.457 CP SECONDS EXECUTION TIME.
```