This is to certify that the

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PERFORMANCE EVALUATION OF COMMERCIAL
CROSSFLOW AND CONCURRENT-FLOW
GRAIN DRYING

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John Cameron Anderson

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F. W. Bakker-Arkema
Major professor

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By

John Cameron Anderson

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ABSTRACT

PERFORMANCE EVALUATION OF COMMERCIAL CROSSFLOW AND CONCURRENT-FLOW GRAIN DRYING

By

John Cameron Anderson

An experimental/simulation study was conducted on the evaluation and the comparison of three commercial continuous-flow corn dryers. Experimental data was collected on two crossflow dryers and one concurrent-flow dryer during the 1983 and 1984 drying seasons. Energy efficiency and grain quality were the two major evaluation criteria.

Air recirculation of part of the cooling and drying air in the crossflow dryer saved at least 15 percent in energy consumption. Concurrent-flow drying produced a 20 percent savings in energy consumption and a 45 percent reduction in breakage susceptibility increase compared to crossflow drying.

Simulation showed that an increase in air recirculation temperature results in a lowering of the airflow rate in a grain dryer, thereby, offsetting the expected improvement in energy efficiency at high inlet moisture contents.

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CHAPTER I

INTRODUCTION

The artificial drying of cereal grains has significant importance. Early harvest reduces field losses, allows for better field conditions, and permits ground preparation for the next season. Harvest planning can make better use of labor and machinery when harvest is not dependent on moisture content fluctuations in the field. Drying enables long-term storage without deterioration allowing higher prices than are common at harvest time. Removal of excess moisture maintains viability of grain, reduces mold damage and provides a better quality product. The use of corn hybrids with longer maturity results in larger yields, but also in higher moisture contents at harvest time. These factors combine to require an energy intensive production system and demonstrate the need for research in the drying of cereal grains and in dryer performance. Approximately 60 percent of the energy used for non-irrigated corn production is required for drying (Bakker-Arkema et al., 1979).

According to FAO (1983), the United States produces approximately 45 percent of the world production of corn on approximately 23 percent of the total acreage devoted to production (see Table 1.).

1.1 Michigan Corn and Grain Production

Corn continues to be Michigan's leading crop in both acreage and value. (see Table 1.1). The 1983 corn crop for grain was valued at

Table 1. Corn Production in the U.S.A. and the World in 1980-82.

Year	1000 Tons		1000 Acres	
	U.S.A.	World	U.S.A.	World
1980	186,055	436,460	73,032	316,329
1981	229,644	496,654	74,700	327,629
1982	235,125	501,938	73,153	324,763

Source: FAO (1983)

Table 1.1. Michigan Corn for Grain Production.

Year	Harvested		$ Value	
	(1,000 Acre)	Bu/A	$/Bu	(Million)
1983	1,800	92	3.35	555
1982	2,740	107	2.55	748
1981	2,800	96	2.39	642

Source: MDA (1984)

555 million dollars down 26 percent from 1982. The 1983 corn acreage decreased sharply due to heavy participation in the Payment In Kind (PIK) Program. Grain acreage in 1983 declined 34 percent and was at the lowest level since 1972.

Nationally, corn production in 1983 totaled 4.2 billion bushels, half as large as the record 1982 crop (8.4 billion bushels) and the smallest crop since 1970 (MDA 1984).

In 1983, Michigan's rank in the nation's agriculture was first in production of all dry beans (29.8%) and navy beans (81.2%), 7th in rye (2.3%), 8th in corn for grain (4.1%) and oats (3.3%), 13th in soybeans (1.9%), and 17th in winter wheat (1.8%) (MDA 1984).

The Michigan Planting and Harvesting Data for 1975-1979 indicates that an average of 40 percent of the corn still has to be harvested after November 3. More than 80 percent of the corn produced in the nation is artificially dried (ASAE, 1978).

1.2 Units

English units are used in this thesis. The research conducted was supported by grants from private industry. Reports in English units were required.

CHAPTER 2

OBJECTIVES

The objectives of this study are:

(i) To collect experimental data on the following corn dryers:

a. an off-farm continuous flow crossflow dryer with cooling-air recirculation and grain exchanger;

b. an on-farm/off-farm continuous flow crossflow dryer with drying/cooling air recirculation and grain tempering;

c. an on-farm single-stage concurrent-flow dryer with counterflow cooler.

(ii) To compare the two crossflow dryers and the concurrent-flow dryer with respect to energy efficiency and grain quality.

(iii) To simulate dryer performance of the off-farm continuous flow crossflow dryer and to generate its performance at standard operating conditions at five, ten, and fifteen points of moisture removal.

CHAPTER 3

LITERATURE REVIEW

3.1 Crossflow Drying

The crossflow dryer is the most prevalent type used in the United States for drying corn (Bakker-Arkema et al., 1978b). This dryer type has a lower initial cost than most other types.

Crossflow dryers incorporate a central plenum surrounded by a grain column. The air moves from the plenum perpendicular across a moving or stationary 12-16" grain column.

Several configurations of commercial crossflow dryers are available. The tower dryer is mounted on a permanent foundation; examples are the Zimmerman and Meyer-Morton. The towers are circular with the surrounding grain column formed of perforated screen (see Figure 3.1.1).

The second configuration has a plenum along the horizontal axis. It can be fixed or portable. Examples are the Farm Fans and the Berico. The main columns are on the two sides of the plenum (see Figure 3.1.2). Both configurations can be operated as continuous flow, multi-stage or batch systems.

The characteristics of the crossflow dryer are (Brooker et al., 1974; Hawk et al., 1978):

1. The grain on the plenum side of the column is overdried while grain on the opposite side is underdried.

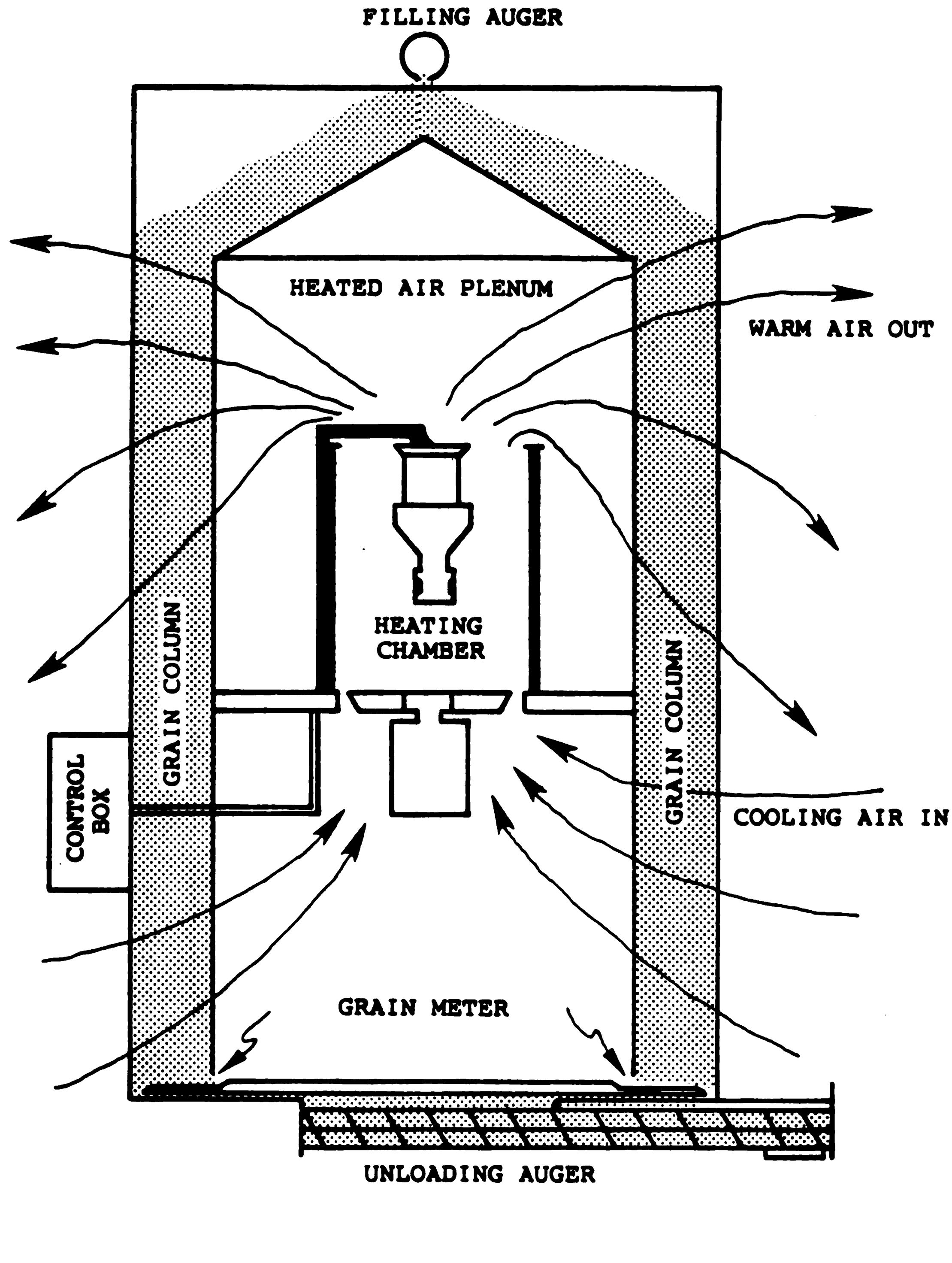

Figure 3.1.1

Crossflow dryer with forced air drying and reversed flow cooling (from Brooker et al., 1974).

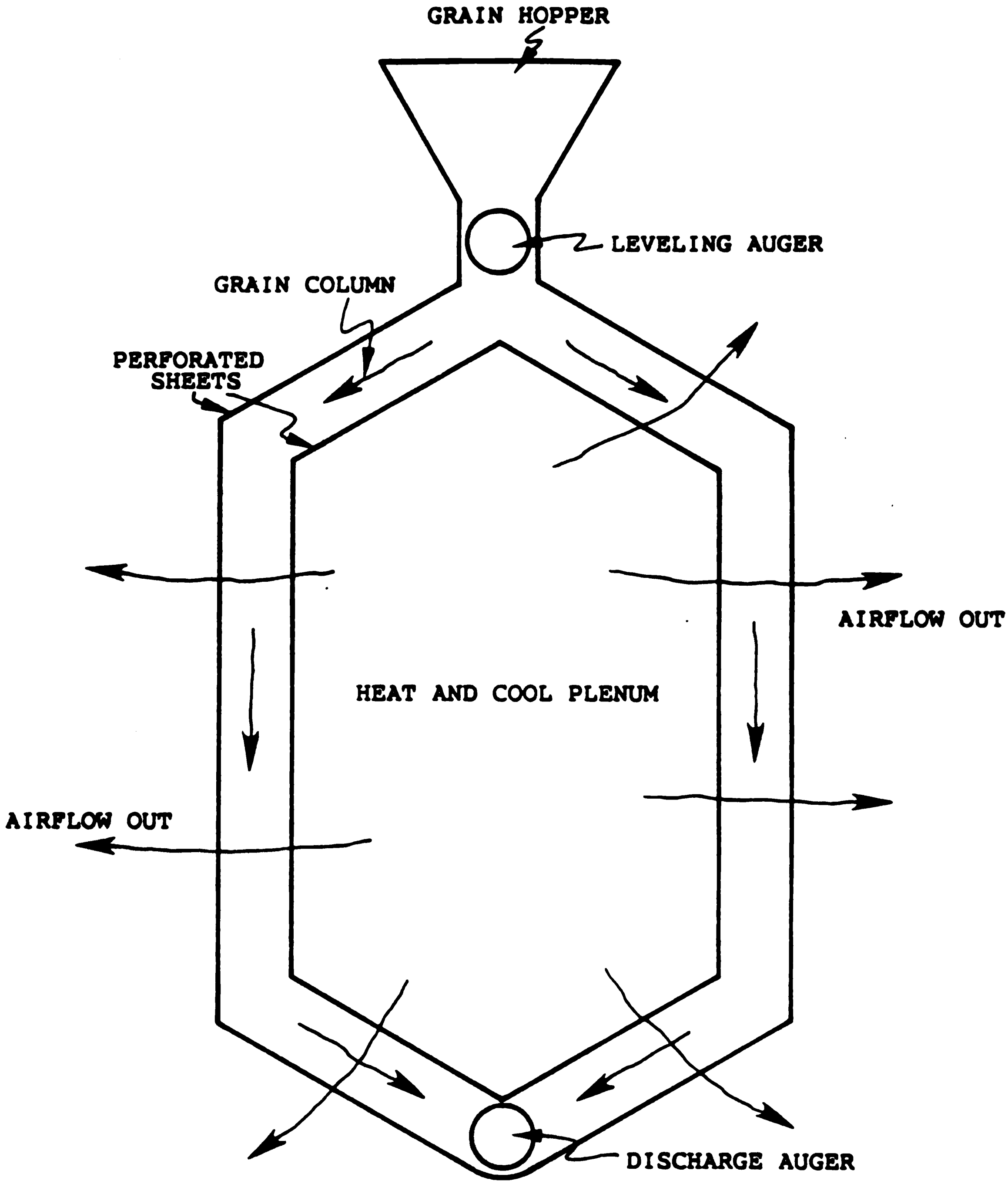

Figure 3.1.2

Batch crossflow dryer.

2. The grain on the plenum side is heated to near the drying air temperature which results in excessive stresses within the grain kernels, when suddenly exposed to ambient air for cooling.

Modern crossflow dryers differ in grain column height, length, and thickness, and in the pattern of air circulation and airflow rates in the drying and cooling sections (Hawk et al., 1978). The objective of the recent design has been to increase energy efficiency while minimizing temperature and moisture gradients across the grain columns.

Additional design modifications incorporated by crossflow dryer manufacturers are (Bakker-Arkema et al., 1982):

1. A grain turning device (called grain exchange or grain turn-flow) which interchanges the plenum side of the grain column to the outside and vice versa such that the wetter grain is moved to the higher temperature plenum side.
2. A tempering section which allows the grain to equalize in moisture and temperature.
3. A differential grain-speed option which consists of a metering device that causes the grain to move faster on the plenum side than on the air-exhaust side of the column.

3.2 Concurrent-Flow Drying

Increased interest in concurrent-flow dryers has been generated due to advantages of improved energy efficiency and grain quality of this dryer type when compared to that of conventional crossflow dryers. The design allows the use of very high inlet air drying temperatures; this results in a higher energy efficiency than in comparable crossflow dryers

(Bakker-Arkema et al., 1972). A schematic and flow diagram of a concurrent-flow dryer with counterflow cooler are illustrated in Figures 3.2.1 and 3.2.2 respectively.

The characteristics (Brooker et al., 1974; Hawk et al., 1978) of concurrent flow dryers are:

1. The air and grain flow in the same direction through the dryer which allows the hottest air to encounter the wettest grain.
2. Drying air temperatures of 300 to 500^{o}F can be used without causing excessively high grain kernel temperatures.
3. Concurrent flow drying is usually combined with a counterflow cooler in which the air and grain flow are in opposite directions; this principle of cooling allows ambient air to first encounter the coolest grain, thereby limiting thermal stresses in the grain.
4. All grain undergoes the same drying treatment unlike in crossflow dryers.
5. The fan delivers air against higher static pressures because of the 2-3 ft. bed depth.

3.3 Grain Tempering

The process of high temperature drying results in the occurrence of moisture and temperature gradients within the individual kernels. Stress cracking occurs when the gradients become too large, thereby increasing the breakage susceptibility of the grain.

Tempering in grain refers to the holding of grain between individual drying stages (for multi-stage dryers), or between drying and cooling stages (for crossflow and combination drying systems).

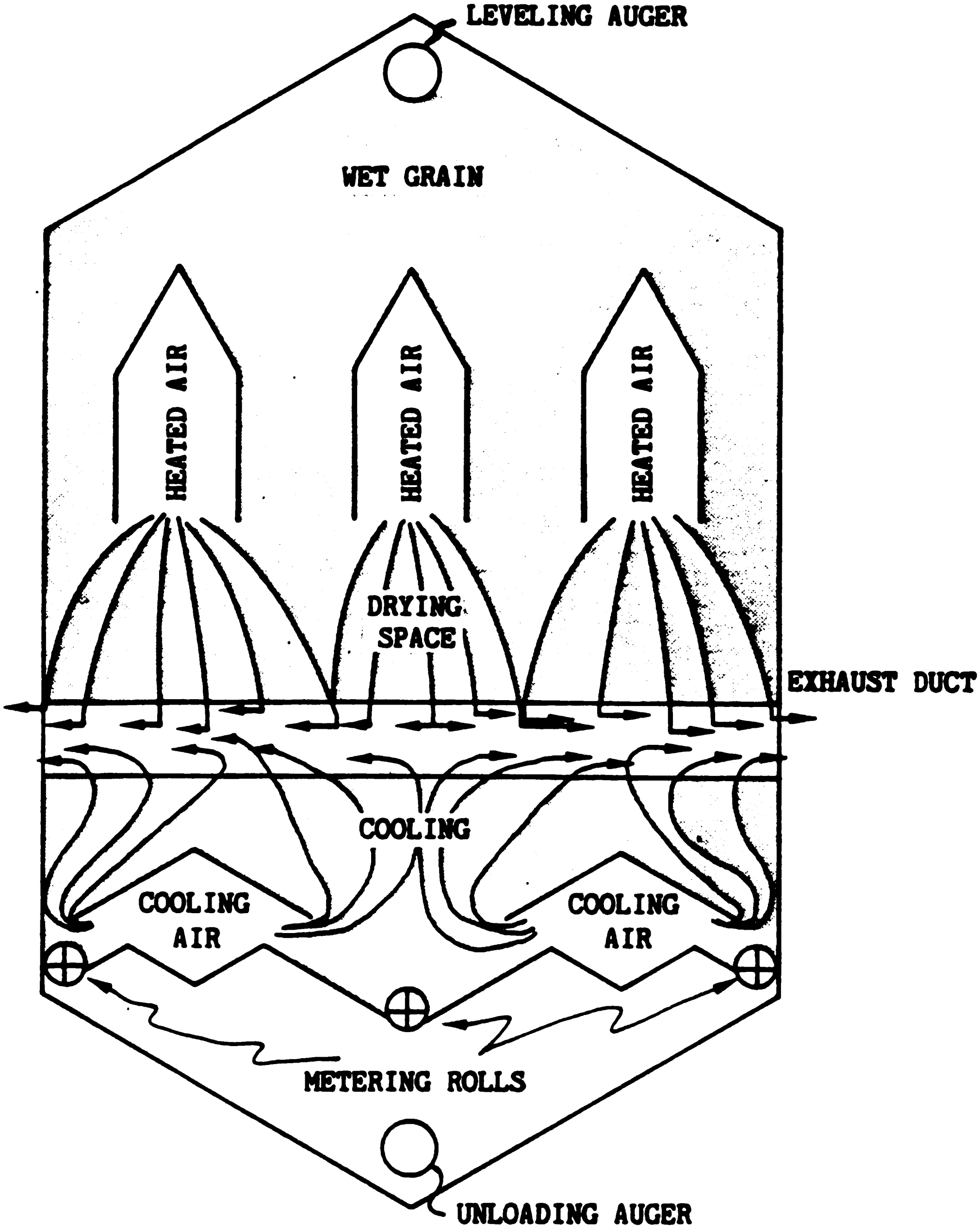

Figure 3.2.1

Schematic of concurrent flow dryer with counter-flow cooler (from Brooker et al., 1974).

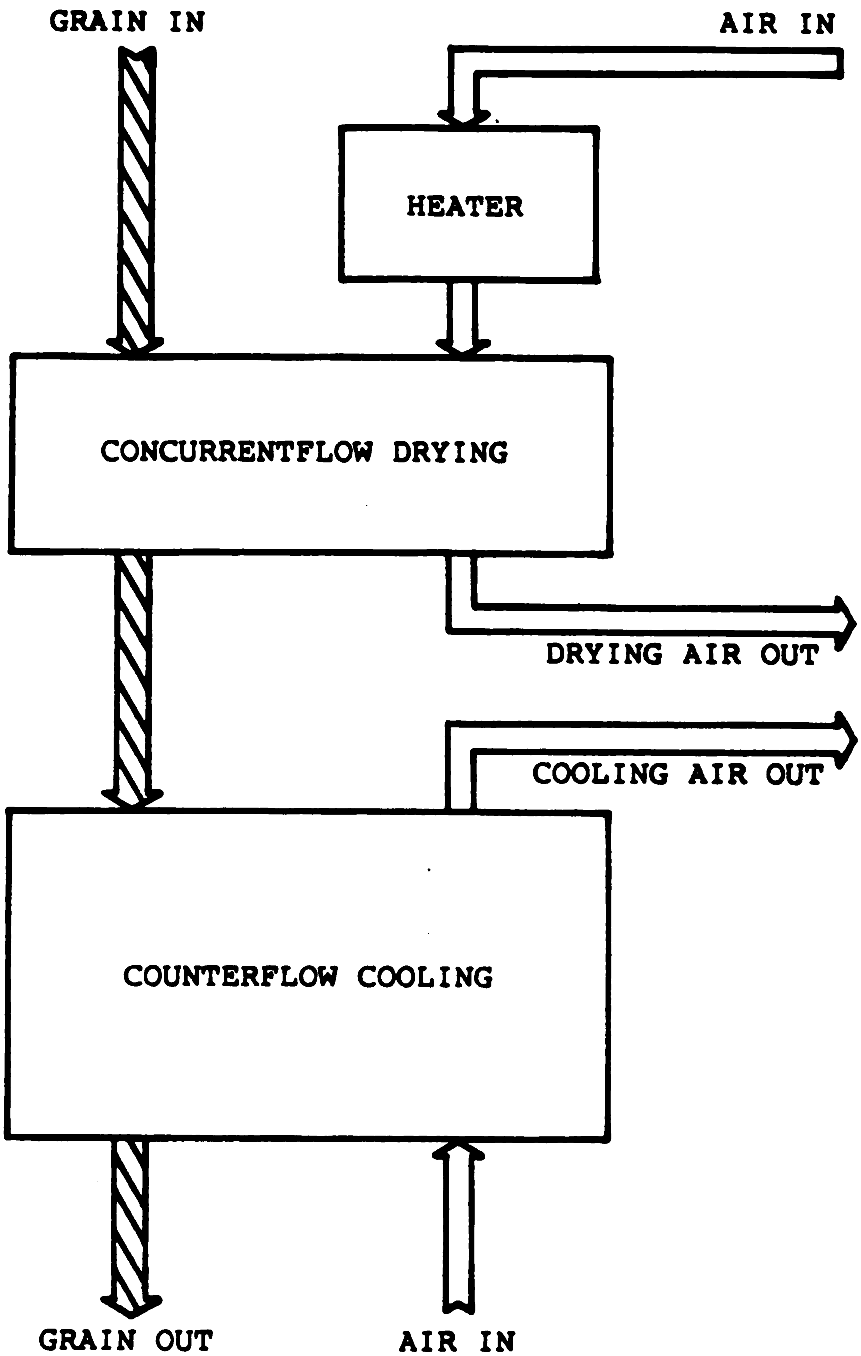

Figure 3.2.2

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

The tempering time, representing the holding period, varies from several minutes (in commercial crossflow dryers) to as much as ten hours (in combination drying systems). Sabbah et al. (1972) concluded that tempering of corn for eight hours after heated air drying at 187°F and 45 cfm per bu resulted in a higher moisture removal rate during cooling than tempering for two, four, or twelve hours. Tempering times used in commercial rice drying vary from approximately ten to twenty four hours in California (Steffe and Singh, 1980). Sokhansanj et al. (1983) concluded the drying characteristics of grain can be used to estimate the tempering period necessary to achieve a reasonably uniform moisture distribution within the grain.

Tempering of grain during the drying process can lead to improved grain quality and reduced energy consumption. However, tempering does require modification in the design of conventional drying equipment.

3.4 Effects of Drying on Grain Quality

Cereal grains in the United States are officially graded under the Federal Grain Standards Act. The grades and grade requirements for corn are shown in Table 3.4.1. Only test weight, moisture content, broken corn and foreign material, and damaged kernels are considered in the United States standard for corn. Desirable properties of high quality shelled corn are (Brooker et al., 1974): (1) low and uniform moisture content, (2) low percentage of stress-cracked, broken and damaged kernels (3) low susceptibility to breakage, (4) high test weight, (5) high starch yield, (6) high oil recovery, (7) high protein quality, (8) high viability, (9) low mold count, and (10) high nutritive value. Not all of these properties are important to every user. The seed corn grower, wet-miller livestock feeder, and grain dealer have different interests. The drying process has an important effect on these quality aspects.

Table 3.4.1. U.S. Numerical grades and sample grade requirements for corn.

Grade	Minimum Test Weight Lb/bu	Maximum Limits			
		Moisture %	Broken Corn and Foreign Material %	Damaged Kernels	
				Total %	Heat-Damaged Kernels %
1	56	14.0	2.0	3.0	0.1
2	54	15.5	3.0	5.0	.2
3	52	17.5	4.0	7.0	.5
4	49	20.0	5.0	10.0	1.0
5	46	23.0	7.0	15.0	3.0

Sample grade shall be corn which does not meet the requirements for any of the grades from No. 1 to No. 5, inclusive; or which contains stones; or which is musty, or sour, or heating; or which has any commercially objectionable foreign odor; or which is otherwise of distinctly low quality.

Source: U.S.D.A. (1978).

3.4.1 Test Weight

The test weight per bushel is used as a measure of grain density. The test weight is determined by weighing a measured volume ($1^1/_8$ quart) and converting the weight to pounds per bushel. Minimum test weights are included in the U.S. Federal Grain Standards.

The test weight of grain usually increases during the drying process (Hall and Hill, 1972). Results show that at high initial moisture contents the test weight of corn may increase by as much as four pounds per bushel. Increasing drying air temperature of high temperature drying reduces the test weight increase associated with the drying (Gustafson and

Morey, 1979). Artificially dried corn has a lower test weight than field dried corn (Peplinski et al., 1975).

The test weight increase during drying depends upon (Brooker et al., 1974): (1) the degree of kernel damage, (2) the initial moisture content, (3) the temperature reached by the grain during the drying process, (4) the final moisture content, and (5) the grain variety. The maximum test weight is reached when the moisture content is between 14 and 16 percent wet basis.

3.4.2 Stress Cracks and Broken Kernels

Thompson and Foster (1963) have defined stress cracks as the cracks in the starchy endosperm within the corn kernel which do not rupture the seed coat. The amount of moisture reduction as well as the rate of drying are related to the extent of stress crack development. Therefore, high temperature - high capacity dryers have a direct influence on stress cracking.

Ross and White (1972) showed that stress cracking decreases as corn is dried from a lower initial moisture content.

The cooling process has a direct effect on the degree of stress cracking. Rapid cooling of high temperature corn causes a high percentage of stress crack development (White and Ross, 1972). Slow cooling or dryeration can significantly reduce the percent of stress cracked kernels.

Harvesting conditions of special interest include moisture content and harvest machine operation. Mechanical damage in the form of broken kernels and small cracks may not immediately effect the market grade of the grain, but will increase the deterioration rate and breakage during subsequent handling.

3.4.3 Breakage Susceptibility

Breakage susceptibility, a problem of corn quality, has gained considerable interest in the past decade. Modern harvesting and drying methods are responsible for producing stress cracks in the corn kernels, thereby increasing breakage susceptibility. A collaborative testing program has been conducted over the past several years by NC-151 to establish a standardized procedure for measuring breakage (Watson et al., 1983). The test compared the Stein breakage tester (impact and abrasion) and the Wisconsin breakage tester (impact). The committee concluded that the Wisconsin breakage tester had consistently the lowest coefficient of variability, was of unique sturdy design, and more suitable for commercial manufacture and use. Mean breakage values of the corn differed over a range of 9 to 30 percent.

The risks involved as breakage susceptibility increases are (Paulson and Hill, 1980; Watson et al., 1983): (1) excessive BCFM, (2) increase in mold and fungi growth, (3) interference with aeration, (4) increase in dust levels and dust explosions, (5) unsuitably for certain food products, (6) non-constant material flow in processing operations, and (7) quality decrease of exports.

Breakage susceptibility changes in corn dried above 18 to 20 percent moisture content are small while those in corn dried below 18 to 20 percent can be large (Gustafson et al., 1978; Gustafson and Morey, 1979, Gustafson and Morey, 1981a).

Thompson and Foster (1963) reported that corn artificially dried with heated air was two to three times more susceptible to breakage than corn dried with natural air. Increasing the drying-air temperature in high temperature drying increases the breakage susceptibility (Gustafson and Morey, 1979).

The breakage susceptibility of corn dried in the concurrent flow dryers was markedly less than that dried in crossflow models (Bakker-Arkema et al., 1981a; Bakker-Arkema et al., 1981b). Gustafson et al. (1981b) reported that a grain turning device reduces the temperature and moisture content gradients in crossflow dryers and thus the breakage susceptibility across the column while it does not significiantly effect the energy requirement. Thin-layer tests showed breakage susceptibility could be reduced by tempering with most of the reduction in the first 30 minutes (Gustafson et al., 1982).

3.5 Energy Efficiency and Capacity

Bakker-Arkema et al. (1978a) defined energy efficiency of a grain dryer or drying process in terms of the energy required to remove a unit weight of moisture from the grain under specific conditions; it is expressed in BTU per pound of water removed. The dryer capacity is reported in wet and dry bushels of corn at 5 or 10 points of moisture removal.

The energy efficiency and capacity of a dryer depend on (Bakker-Arkema, 1985a): (1) the dryer type, (2) the grain type, (3) the grain hybrid, (4) the initial temperature and moisture content of the grain, (5) the final temperature and moisture content of the grain, (6) the drying air temperature, (7) the BCFM of the grain, (8) the environmental conditions (air temperature and humidity), (9) the type of fuel, (10) the dryer design and control, and (11) the management of the drying system.

Bakker-Arkema et al. (1973, 1978b) proposed a Dryer Performance Evaluation Index (DPEI).for calculating energy requirements. The DPEI relates the total energy required by a dryer to remove one pound of moisture from the grain under a set of specific conditions. The total energy includes the energy required to heat the drying air, to run the drying and cooling fans, and to move the grain.

Energy efficiencies of crossflow dryers range from 1700 to over 3000 BTU per pound of water; concurrent flow dryers range from 1400 to 1800 BTU per pound of water. Recycling the cooling air and part of the drying air greatly decreases the energy requirement of crossflow dryers.

The United States Dryer Manufacturers' Council has been unable to agree on a standard test for evaluation of dryer performance.

CHAPTER 4

EXPERIMENTAL

The three dryers compared in this study are:

1. An off-farm continuous flow crossflow dryer (the Zimmerman ATP 5000) with cooling-air recirculation and grain exchanger.
2. An on-farm/off-farm continuous flow crossflow dryer (the Meyer Morton 850 modified) with drying/cooling air recirculation and grain tempering.
3. An on-farm single-stage concurrent flow dryer (the M&W 450R) with counterflow cooler.

4.1 Zimmerman ATP 5000

A tower type crossflow dryer, model ATP 5000, manufactured by Zimmerman Equipment Company, Litchfield, IL is illustrated in Figure 4.1.1. The dryer consists of a 66.8 ft heating section and a 18.5 ft cooling section. The 12 inch column thickness is uniform over the entire length of the dryer. The outside dryer diameter is 23.25 feet. The dryer specifications are tabulated in Table 4.1.1.

At the mid-point in the heating section the grain passes through a grain exchanger. The grain column is split so that the inside and outside halves of the grain column are interchanged. The grain is tempered for 2 to 5 minutes in this section, depending on the grain velocity through the dryer.

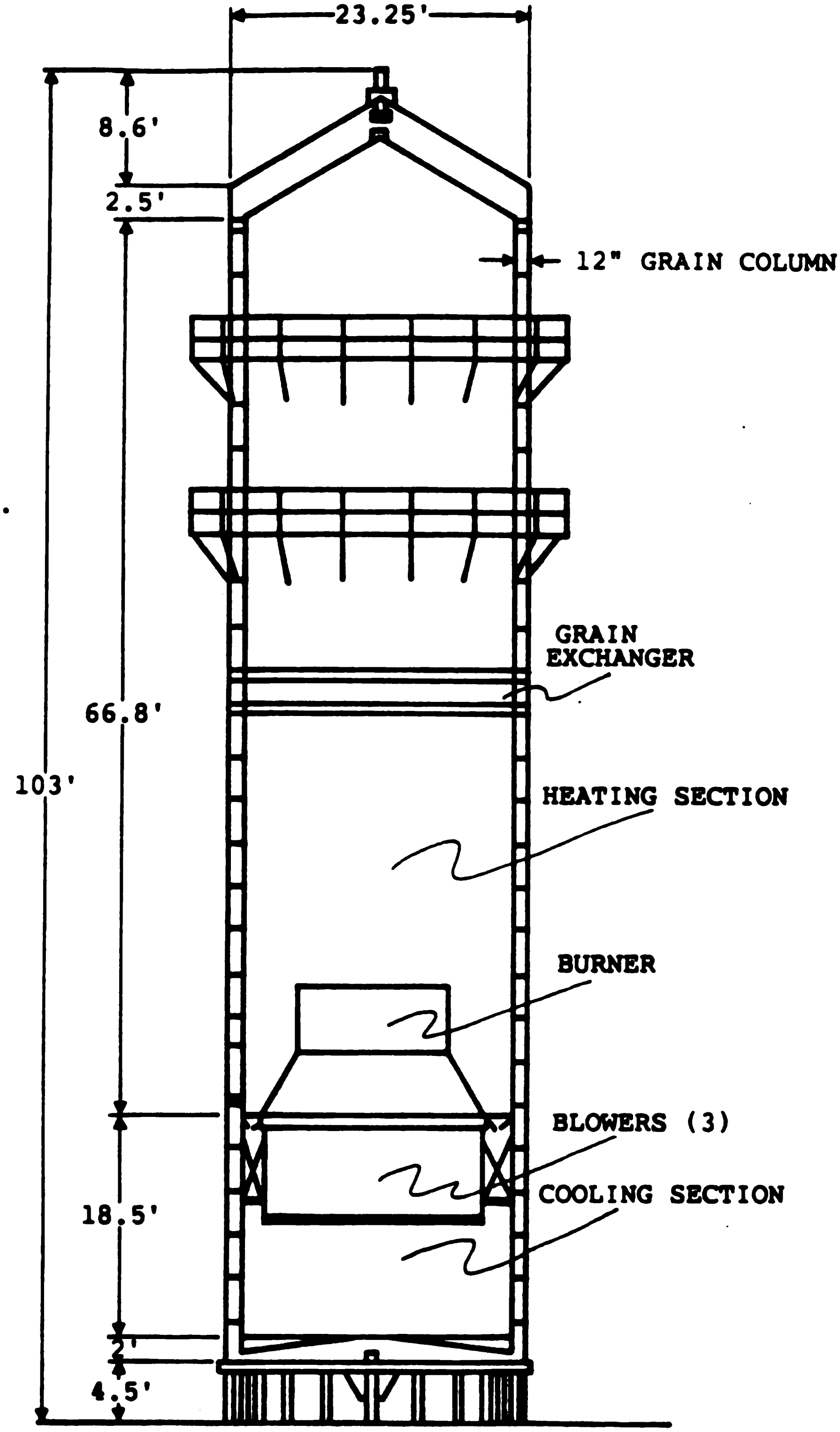

Figure 4.1.1

Schematic of Zimmerman ATP5000 Dryer.

Table 4.1.1. Dryer manufacturer's specifications for the Zimmerman ATP 5000.

Airflow heat section, cfm/bu	69
Airflow cooling section, cfm/bu	132
Airflow heat section, cfm/ft^2	61
Airflow cooling section, cfm/ft^2	111
Static pressure heat section, in. of WC	1.5
Static pressure cooling section, in. of WC	1.5
Column cross sectional area, ft^2	70.1
Column width, in.	12
Grainflow, ft/hr at 5 pnt moisture removal	85.3
Recommended drying temperature, ^{o}F	180
Rated capacity 20%-15% MC, bu/hr	5,000
Retention time at rated capacity, hr	1
Burner capacity, million of BTU/hr	54.2
Fuel type	Nat. Gas

The airflow direction is reversed in the cooling section since the blowers and motors are internal to the structure. Air from the cooling section is blended with ambient air drawn through louvered doors in the cooling section.

The air system consists of three 100 HP motors and three centrifugal fans. The fans (number 8660 series 8000 tubular centrifugal) are manufactured by Barry Blower, Minneapolis, MN.

4.2 Meyer Morton 850 Modified

A tower type crossflow dryer, model 850 modified, manufactured by Meyer Morton Company, Morton, IL is illustrated in Figure 4.2.1. The

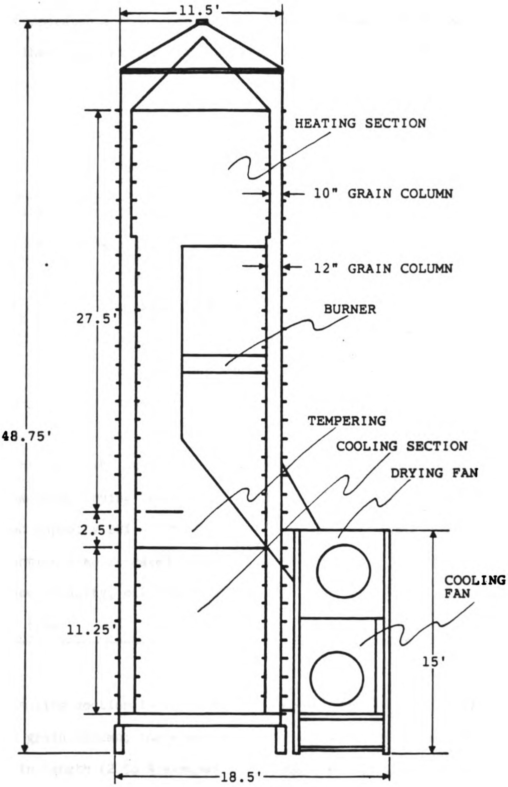

Figure 4.2.1

Schematic of the Meyer Morton 850 Modified Dryer.

dryer incorporates a "heat recovery enclosure package" which is not shown in the illustration. The specifications are tabulated in Table 4.2.1.

Table 4.2.1. Dryer manufacturer's specifications for the Meyer Morton 850 Modified.

Airflow heat section, cfm/bu	122
Airflow cooling section, cfm/bu	142
Airflow heat section, cfm/ft^2	102
Airflow cooling section, cfm/ft^2	126
Static pressure heat section, in. of WC	3.0
Static pressure cooling section, in. of WC	3.0
Column cross sectional area, ft^2	33
Column widths, in.	10 & 12
Grainflow, ft/hr at 5 point moisture removal	65.5
Recommended drying temperature, ^{o}F	230
Rated capacity 20% - 15% MC, bu/hr	1400
Retention time at rated capacity, hr	0.63
Burner capacity, million of BTU/hr	8.7
Fuel type	LP

The heating section is 27.5 feet in length. The upper 8.75 feet has a 10 inch grain column; the remaining is 12 inch. A tempering section of 2.5 feet in length (2 to 4 minutes in drying time) follows the heat section. The outside dryer diameter is 11.5 feet.

The cooling section is 11.25 feet in length with a column thickness of 12 inches.

The heating and cooling sections have individual fans. The drying air fan for the heating section is driven by a 60 HP motor. Air for this fan is a combination of ambient air and recycled air (cooling plus part of drying air) from the heat recovery enclosure. The cooling fan (ambient air) is driven by a 25 HP motor. The airflow in the heating and cooling section is in the same direction (no reversal). The fans (size 40 1/4) are manufactured by Chicago Blower, Glendale Heights, IL.

4.3 M&W 450R

A M&W concurrent flow dryer with counterflow cooler, model 450R, manufactured by the M&W Gear Company, Gibson City, IL is illustrated in Figure 4.3.1. The specifications are tabulated in Table 4.3.1. As the grain passes from the wet storage section to the drying section, it is preheated to some extent due to the preheat exhaust ducts that are located above the hot air plenums. The grain continues to flow between the hot air plenums until it reaches the drying section where the concurrent-flow process takes place. Air is exhausted from the drying section through the hot air exhaust ducts at the base of this section.

The air flow is reversed in the cooling section according to the counterflow design. Cooling air exhaust ducts are located beneath the hot air exhaust ducts. The cooling air enters through the cooling air plenums at the base of the cooling section just before the grain reaches the metering rolls.

The dryer is PTO driven by a 150 HP tractor. The dryer requires an electric motor of 75 HP. The fans (PLR SW wheel) are manufactured by Mechanovent Corporation, LaPorte, IN.

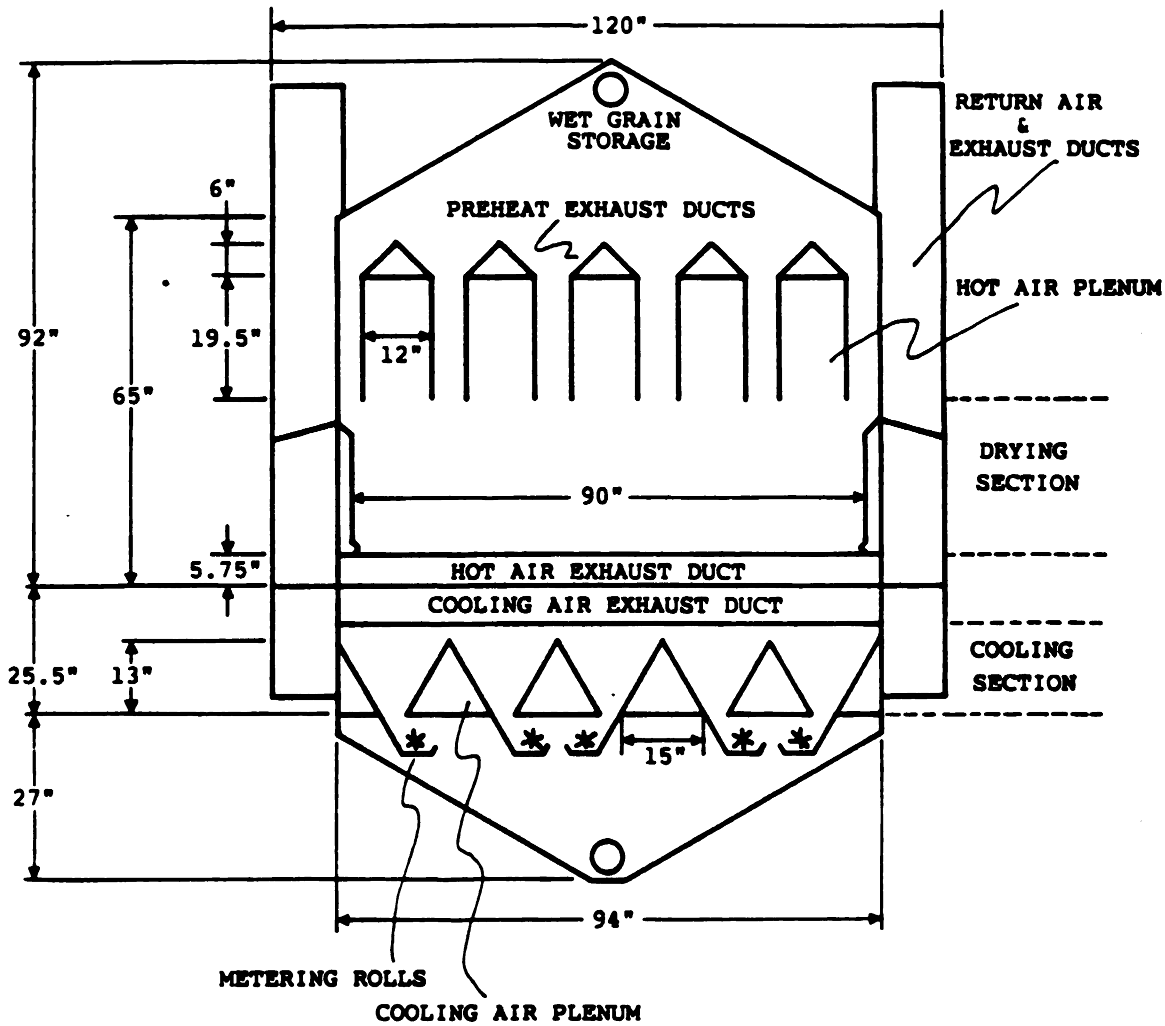

Figure 4.3.1

Schematic of the M&W 450 R Dryer.

Table 4.3.1. Dryer manufacturer's specifications for the M&W 450R.

Airflow heat section, cfm/bu	76
Airflow cooling section, cfm/bu	62
Airflow heat section, cfm/ft^2	152
Airflow cooling section, cfm/ft^2	80
Static pressure heat section, in. of WC	9.5
Static pressure cooling section, in. of WC	9.5
Bed depth heat section, ft	2.75
Bed depth cooling section, ft	2.13
Cross sectional area, ft^2	150
Grain flow, ft/hr at 5 point moisture removal	7
Recommended drying temperatue, ^{o}F	300
Rated capacity 20% - 15% MC, bu/hr	670
Retention time at rated capacity, hr	0.7
Burner capacity, million of BTU/hr	6
Fuel type	LP

4.4 Dryer Instrumentation and Measurements

The actual capacity and energy efficiency of the grain dryer operating under prevailing conditions were determined by measuring the following parameters:

1. Grainflow rate
2. Inlet and outlet moisture content
3. Inlet and outlet test weight and BCFM
4. Change in grain quality
5. Inlet and outlet grain temperature
6. Fuel and energy consumption
7. Ambient temperature
8. Ambient relative humidity
9. Drying air temperature.

Moisture content of the samples was measured hourly by the standard oven method (Brooker et al., 1974).

Test weight of the corn samples was determined according to standard practice (Brooker et al., 1974).

Breakage susceptibility determinations were performed using the Wisconsin breakage tester (Watson et al., 1983).

Ambient and drying air temperatures were measured with cooper-constantan thermocouples and recorded on a Digistrip II recorder manufactured by Kaye Instruments, Inc., Bedford, MA. Relative humidity was determined by using a dry bulb-wet bulb thermometer. Inlet and outlet grain temperatures were measured with a thermometer with $1^{o}F$ division.

Static pressure was measured in units of water column height. A Utube manometer was used. The airflow rates were determined from fan curves supplied by the fan manufacturers or from the Shedd airflow versus static pressure curve (Brooker et al., 1974).

CHAPTER 5

DRYING SIMULATION

Simulation models for evaluating the energy and capacity performance of grain dryers are of benefit to dryer manufacturers and designers in determining optimum design, in predicting the effects of a change in the various drying parameters, and in reducing exhaustive experimental testing. Deep-bed simulation models have been developed at Michigan State University by Bakker-Arkema et al.(1974) The models are based on the laws of heat and mass transfer and the following assumptions:

(1) no appreciable volume shrinkage occurs during the drying process;

(2) no temperature gradients exist within the grain kernels;

(3) particle to particle conduction is negligible;

(4) air flow and grain flow are plug-type;

(5) the dryer walls are adiabatic with negligible heat capacity;

(6) dT/dt and dH/dt are negligible compared to dT/dx and dH/dx (d used as differential symbol);

(7) the heat capacity of moist air and of grain are constant during the short time periods;

(8) accurate thin layer, moisture equilibrum isotherm and latent heat of vaporization equations are available.

The latest version of the MSU crossflow, and concurrent flow drying models is presented by Rodriguez (1982) and Fontana (1983).

The MSU simulation drying models allow the calculation of grain temperature, air temperature, air absolute humidity, air relative humidity, and grain moisture content as a function of time and position in the drying/cooling sections. The models are general and can be used by dryer manufacturers with the aid of an educational institution such as Michigan State University.

CHAPTER 6

RESULTS AND DISCUSSION

6.1 Experimental Results

The 1983 and 1984 experimental drying test results conducted with the crossflow dryers and with the concurrent flow dryer are presented in Tables 6.1.1.1 through 6.3.2.4.

6.1.1 Zimmerman ATP 5000

The partial data of two experimental tests conducted with the Zimmerman ATP 5000 are tabulated in Table 6.1.1.1.

Table 6.1.1.1. Drying air temperature, retention time, and breakage susceptibility increase of the Zimmerman ATP 5000 dryer.

Test	Moisture Content (% w.b.) In	Moisture Content (% w.b.) Out	Drying Air Temp. (°F) (BTU/lb)	Retention Time (hrs.)	Breakage Susceptibility Increase *(%)
1	25.3	18.5	158°F	1.4	6.5
2	25.1	14.9	226°F	1.9	15.9

* the MC at the breakage test determination was 9.3% (w.b.) for Test 1; 10.2% (w.b.) for Test 2.

Test No. 1 is included only for the comparison of breakage susceptibility increase. It was run only for a short period of time (less than 9 hours) due to the extraordinary dry fall conditions in Michigan in 1983. The pertinent conditions for the breakage susceptibility comparison for

Test No. 1 are: average inlet moisture content 25.3% w.b., average outlet moisture content 18.5% w.b., average retention time 1.4 hours, grain flow rate 61 feet/hour, and average drying air temperature 158°F. The breakage susceptibility increase was a low 6.5 percent.

Test No. 2 lasted over 19 hours. Tables 6.1.1.1 and 6.1.1.2 contain the experimental data. About 47,000 bushel of corn was dried with an initial moisture content ranging from 24.5 to 25.7 percent wet basis, and an average MC of 25.1 percent. The average retention time was 1.9 hours. The inlet BCFM ranged from 0.4 to 0.8 percent, the test weight from 51.8 to 52.6 pound/bushel. The final moisture content varied from 13.5 to 16.3 percent, with an average of 14.9 percent. The grain flow rate was 44.9 feet/hour which translates to a wet bushel capacity of 2,611 bushel/hour, assuming an average test weight of 52.2 pound/bushel. Using a standard 56 pound/bushel test weight, a capacity of 2,434 bushel/hour was measured. The dry bulb temperature varied from 42 to 60°F; the average relative humidity was 75 percent. The drying air temperature was an average 226°F. The average inlet grain temperature was 67°F, the outlet grain temperature 63°F. A total of 315,716 pounds of water was evaporated in the 19.3 hour drying process from a average of 25.1 to an average of 14.9 percent. Fuel consumption was 31,640 cubic feet/hour. The energy efficiency (excluding electricity) was 1934 BTU/pound of water.

The grain quality deterioration during the drying process in Test 2 was 15.9 percent in terms of the breakage susceptibility increase. The higher value is due to the higher drying air temperature and the lower final moisture content in Test 2 as compared to Test 1.

The energy cost in terms of cents per bushel per percentage point of

Table 6.1.1.2. Operating conditions during drying of corn in Test No.2 of the Zimmerman ATP 5000 dryer.

Grain Parameters	
Average inlet MC, % w.b.	25.1
Average outlet MC, % w.b.	14.9
Average inlet grain temperature, °F	67
Average outlet grain temperature, °F	63
Average inlet BCFM, %	0.6
Average test weight in, pound/bushel	52.2
Average test weight out, pound/bushel	54.0
Wet weight corn, pound	2,630,253
Initial breakage[1], %	17.0
Air Parameters	
Average drying temperature, °F	226
Average ambient dry bulb temperature, °F	51
Average ambient relative humidity, %	75
Airflow rates	
Heat section, cfm/bushel	61
Cool section, cfm/bushel	127
Static pressure	
Heat section, in. of w.c.	1.5
Cool section, in. of w.c.	1.7
Energy Use	
Fans and augers, kWh/hour	244.0
Natural gas, cubic feet/hour	31,640
Performance Data	
Temperature rise through recycle, ΔT °F	41
Test duration, hour	19.3
Average MC decrease, % w.b.	10.2
Average retention time, hour	1.9
Capacity, wet bushel/hour	2611
Capacity, dry bushel/hour	2221
Capacity, wet bushel/hour at 56 pound	2434
Capacity, dry bushel/hour at 56 pound	2142
Energy efficiency excl. elect., BTU/pound of water	1934
Energy efficiency incl. elect., BTU/pound of water	1985
Breakage susceptibility increase[1], %	15.9
Energy cost[2], ¢/bushel-point	.87

1. Breakage test determined at average MC of 10.2% w.b.
2. Based on 8.55 ¢/kWh, $6.15/10^6 BTU, and 56 pound/bushel.

moisture removal was 0.87 (¢/bu pnt). This figure is based on the prevailing ambient conditions, the average moisture decrease and the grain temperatures at the time of Test 2, and on electrical and natural gas energy costs of 8.55 ¢/kWh and \$6.15/10^6 BTU, respectively.

The ATP 5000 was operated during Test 2 at a drying air temperature far surpassing the value recommended by the dryer manufacturer (226°F vs 185°F). This effected positively the dryer capacity (2142 dry bushel at 10.2 pnt moisture removal) and the energy consumption (1985 BTU/lb), but negatively the breakage susceptibility increase (15.9%). The rated capacity is 3000 wet bushel at 10 pnt removal versus the measured 2434 wet bushel at a final moisture content of 14.9 percent.

Note that the temperature of the air mixture of ambient and recycled air was 41°F above ambient. In a conventional dryer the drying air would have been heated from 51°F to 226°F (a ΔT of 175°F); in the ATP 5000, the temperature rise was from 92 to 226°F (a ΔT of 134°F). Thus, a savings of about 23 percent in fossil fuel resulted, assuming the moisture removal rate was not affected.

Temperature distribution of the inlet drying air and outlet exhaust air at different levels of column height in the ATP 5000 is shown in Table 6.1.1.3. Note that approximately a 30 to 40°F temperature difference exists in the heating section. The minimum temperature was 202°F, the maximum temperature 240°F, and the average drying air temperature 226°F.

Table 6.1.1.3. Temperature distribution in Test No. 2 of inlet drying air and outlet exhaust air at different levels of column height in the Zimmerman ATP 5000 dryer.

Location*	Inlet Air (^{o}F)	Exhaust Air (^{o}F)
1	236	87
2	240	98
3	202	103
4	51	124

* Location from the top of dryer, given in feet of column depth:

Location 1	6.7 feet	Heating Section
Location 2	20.0 feet	Heating Section
Location 3	63.3 feet	Heating Section
Location 4	76.0 feet	Cooling Section (mid-point)

6.1.2 Meyer Morton 850 Modified

Three experimental tests were conducted with the Meyer Morton 850 modified dryer. Test 1 was conducted using the dryer as designed by the manufacturer. For Test 2, a design change was made to recover part of the exhaust drying air. The changes included: (1) closing the ambient air louvers to the heating section fan, and (2) closing four louvers (13%) in the heat recovery enclosure. Test 3 was conducted with 10 louvers (33.3%) closed in the recovery enclosure; in addition, a platform was positioned such that the top 12.5 feet of the drying section was exhausted while 15 feet was recycled to the drying fan. (See Figure 6.1.2.1). The platform was necessary to eliminate a chimney effect in the heat recovery enclosure.

The effect of the air-recirculation design modifications on the energy efficiency of the 850 is illustrated in Table 6.1.2.1. Tests 1 and 2 can be compared directly since they were conducted in the same year (1983) under similar ambient and moisture-removal conditions. Recycling

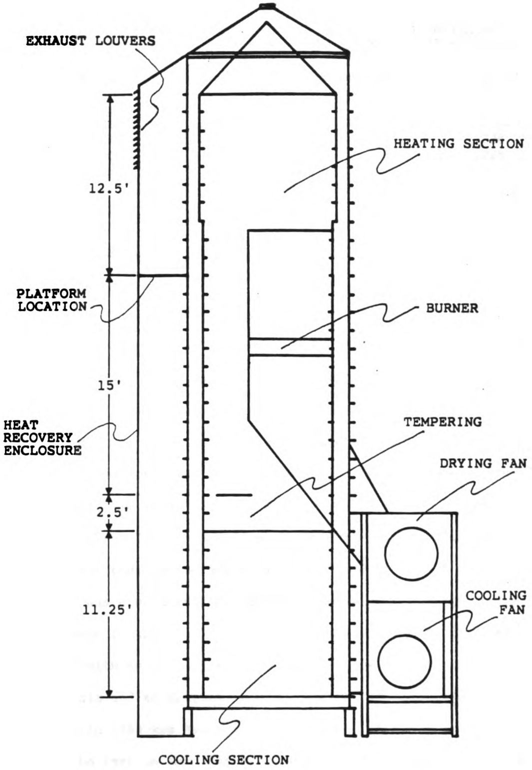

Figure 6.1.2.1

Schematic of the Meyer Morton 850 Modified Dryer with Heat Recovery Enclosure and Platform.

Table 6.1.2.1. Energy efficiency, retention time, and drying air temperature of the Meyer Morton 850 modified dryer.

Test	Moisture Content (% w.b.) In	Out	Energy Efficiency (BTU/lb)	Retention Time (hrs)	Drying Air (^{o}F)
1	29.7	11.2	2124	1.7	228
2	28.4	12.0	1772	1.8	226
3	21.1	14.2	1973	1.1	231

of additional dryer exhaust air improved the dryer efficiency about 17 percent (2124 versus 1772 BTU/lb). It is not clear from the data if the platform and additional closing of extra louvers for Test 3 further improved the energy efficiency. Since the corn in 1984 during Test 3 had a much lower initial moisture content than in 1983 (Tests 1 and 2), a direct comparison of Test 3 with Tests 1 and 2, is not valid.

Tests 1 and 2 are short time tests (7.5 and 4.0 hrs, respectively). The duration of the tests was limited due to the small volume of the LP tank. Therefore, Tables 6.1.2.2 and 6.1.2.3 will not be discussed in detail. Test 3 (see Table 6.1.2.4) with the Meyer Morton 850 constitutes data of a 10-hour test period and will be analyzed.

Test No. 3 was considered the optimal experimental run due to the improvements made in the heat recovery enclosure. About 8,000 bushel of corn was dried with an initial moisture content ranging from 20.2 to 21.9 percent wet basis and an average moisture content of 21.1 percent. The average retention time was 1.1 hours. The inlet BCFM ranged from 0.4 to 1.0 percent; the test weight from 52.9 to 54.8 pound/bushel. The final moisture content varied from 13.4 to 15.1 percent, with an average 14.2 percent.

Table 6.1.2.2. Operating conditions during drying of corn in Test No. 1 of the Meyer Morton 850 modified dryer.

Grain Parameters	
Average inlet MC, % w.b.	29.7
Average outlet MC, % w.b.	11.2
Average inlet grain temperature, ^{o}F	43
Average outlet grain temperature, ^{o}F	49
Average inlet BCFM, %	1.3
Average test weight in, pound/bushel	47.3
Average test weight out, pound/bushel	47.7
Wet weight corn, pound	178,623
Initial breakage[1], %	30.8
Air Parameters	
Average drying temperature, ^{o}F	228
Average ambient dry bulb temperature, ^{o}F	45
Average ambient relative humidity, %	80
Airflow rates	
Heat section, cfm/bushel	91
Cool section, cfm/bushel	117
Static pressure	
Heat section, in. of w.c.	3.2
Cool section, in. of.w.c.	3.4
Energy Use	
Fans and augers, kWh/hour	69.6
LP gas, pound/hour	481
Performance Data	
Temperature rise through recycle, ΔT ^{o}F	15
Test duration, hour	7.5
Average MC decrease, % w.b.	18.5
Average retention time, hour	1.7
Capacity, wet bushel/hour	506
Capacity, dry bushel/hour	397
Capacity, wet bushel/hour at 56 pound	427
Capacity, dry bushel/hour at 56 pound	338
Energy efficiency excl. elect., BTU/pound of water	2076
Energy efficiency incl. elect., BTU/pound of water	2124
Breakage susceptibility increase[1], %	25.5
Energy cost[2], ¢/bushel-point	.88

1. Breakage test determined at average MC of 9.3% w.b.
2. Based on 8.55 ¢/kWh, \$6.15/10^{6} BTU, and 56 pound/bushel.

Table 6.1.2.3. Operating conditions during drying of corn in Test No. 2 of the Meyer Morton 850 modified dryer.

Grain Parameters	
Average inlet MC, % w.b.	28.4
Average outlet MC, % w.b.	12.0
Average inlet grain temperature, ^{o}F	55
Average outlet grain temperature, ^{o}F	55
Average inlet BCFM, %	0.6
Average test weight in, pound/bushel	48.7
Average test weight out, pound/bushel	49.8
Wet weight corn, pound	94,592
Initial breakage[1], %	28.9
Air Parameters	
Average drying temperature, ^{o}F	226
Average ambient dry bulb temperature, ^{o}F	51
Average ambient relative humidity, %	75
Airflow rates	
Heat section, cfm/bushel	91
Cool section, cfm/bushel	117
Static Pressure	
Heat section, in. of w.c.	3.2
Cool section, in. of w.c.	3.4
Energy Use	
Fans and augers, kWh/hour	69.6
LP gas, pound/hour	350
Performance Data	
Temperature rise through recycle, ΔT ^{o}F	32
Test duration, hour	4
Average MC decrease, % w.b.	16.4
Average retention time, hour	1.8
Capacity, wet bushel/hour	486
Capacity, dry bushel/hour	387
Capacity, wet bushel/hour at 56 pound	423
Capacity, dry bushel/hour at 56 pound	344
Energy efficiency excl. elect., BTU/pound of water	1718
Energy efficiency incl. elect., BTU/pound of water	1772
Breakage susceptibility increase[1], %	27.1
Energy cost[2], ¢/bushel-point	.76

1. Breakage test determined at average MC of 9.3% w.b.
2. Based on 8.55 ¢/kWh, \$6.15/10^6 BTU, and 56 pound/bushel.

Table 6.1.2.4. Operating conditions during drying of corn in Test No. 3 of the Meyer Morton 850 modified dryer.

Grain Parameters	
Average inlet MC, % w.b.	21.1
Average outlet MC, % w.b.	14.2
Average inlet grain temperature, °F	43
Average outlet grain temperature, °F	52
Average inlet BCFM, %	0.7
Average test weight in, pound/bushel	53.8
Average test weight out, pound/bushel	54.5
Wet weight corn, pound	438,418
Initial breakage[1], %	17.8
Air Parameters	
Average drying temperature, °F	231
Average ambient dry bulb temperature, °F	41
Average ambient relative humidity, %	77
Airflow rates	
Heat section, cfm/bushel	91
Cool section, cfm/bushel	117
Static pressure	
Heat section, in. of w.c.	3.0
Cool section, in. of w.c.	3.4
Energy Use	
Fans and augers, kWh/hour	69.6
LP gas, pound/hour	308
Performance Data	
Temperature rise through recycle, ΔT °F	74
Test duration, hour	10
Average MC decrease, % w.b.	6.8
Average retention time, hour	1.1
Capacity, wet bushel/hour	815
Capacity, dry bushel/hour	740
Capacity, wet bushel/hour at 56 pound	783
Capacity, dry bushel/hour at 56 pound	720
Energy efficiency excl. elect., BTU/pound of water	1905
Energy efficiency incl. elect., BTU/pound of water	1973
Breakage susceptibility increase[1], %	22.6
Energy cost[2], ¢/bushel-point	.88

1. Breakage test determined at average MC of 10.2% w.b.
2. Based on 8.55 ¢/kWh, $6.15/10^6 BTU, and 56 pound/bushel.

The grainflow rate in Test 3 was 37.5 feet/hour which is equivalent to a wet bushel capacity of 815 bushel/hour assuming an average test weight of 53.8 pound/bushel. At the standard 56 pound/bushel test weight, a capacity of 783 bushel/hour is measured. The dry bulb temperature varied from 35 to 45^{o}F; the average relative humidity was 77 percent. The drying air temperature was an average 231^{o}F. The average inlet grain temperature was 43^{o}F; the outlet grain temperature 52^{o}F.

A total of about 34,900 pounds of water was evaporated in Test 3 in the 10 hour process from an average of 21.1 to an average of 14.2 percent. The L.P. gas used in the process was 3080 pounds. The energy efficiency (excluding electricity) was 1905 BTU/pound of water. Fuel consumption was 308 pound/hour.

The grain quality deterioration in Test 3 during the drying process resulted in a breakage susceptibility increase of 22.6 percent. [Moisture at the Wisconsin breakage test determination was an average 10.2 percent, wet basis].

The energy cost in terms of cents per bushel per percentage point moisture removal was 0.88 (¢/bu pnt). This figure is based on the prevailing ambient conditions, the average moisture decrease, and the grain temperatures at the time of Test 3, and on electrical and LP gas energy costs of 8.55 ¢/kWh and $6.15/10^{6} BTU, respectively.

The 850 was operated during Test 3 at a drying air temperature of 231^{o}F. The high inlet air temperature effected positively the dryer capacity (720 dry bushel at 6.8 pnt moisture removal) and the energy consumption (1973 BTU/lb), but negatively the breakage susceptibility increase (22.6%).

Note that the temperature of the air mixture of ambient and recycled air was 74°F above ambient. In a conventional dryer the drying air would have been heated from 41°F to 231°F (a ΔT of 190°F); in the 850 the temperature rise was from 115°F to 231°F (a ΔT of 116°F). Thus, a savings of about 39% in fossil fuel resulted assuming the moisture removal rate was not affected.

Temperature distribution of the inlet drying air and outlet exhaust air at different levels of column height in the 850 is shown in Table 6.1.2.5. Note that the temperature distribution in the heating section is very uniform.

Table 6.1.2.5. Temperature distribution in Test No. 3 of inlet drying air and outlet exhaust air at different levels of column height in the Meyer Morton 850 modified dryer.

Location*	Inlet Air (°F)	Exhaust Air (°F)
1	230	105
2	231	111
3	230	130
4	41	140

*Location from the top of the dryer, given in feet of column depth:

Location 1	3.75 feet	Heating Section
Location 2	16.25 feet	Heating Section
Location 3	26.25 feet	Heating Section
Location 4	36.25 feet	Cooling Section (mid point)

6.1.3 M&W 450R

The data of two experimental tests conducted with the M&W 450R are tabulated in Table 6.1.3.1. The tests were conducted under similar conditions except for the ambient air temperature, the test duration, and approximately 20°F difference in average drying air temperature. The difference in energy efficiency associated with the test was due in part to the 33°F difference in the ambient temperature.

The duration of Test 1 was limited due to corn supply which resulted in a test of approximately 10 hours. Table 6.1.3.2 will not be discussed in detail. Test 2 (see Table 6.1.3.3) with the M&W 450R dryer constitutes data of approximately a 17 hour period; it will be analyzed in detail.

Table 6.1.3.1. Energy efficiency, retention time, drying air temperature and ambient air temperature of the M&W 450R dryer.

Test	Moisture Content (% w.b.) In	Out	Energy Efficiency (BTU/lb)	Retention Time (hrs)	Drying Air Temperature (°F)	Ambient Air Temperature (°F)
1	31.3	20.0	1740	1.4	282	32
2	30.2	17.7	1470	1.7	263	65

In Test 2 about 5000 bushel of corn was dried with the initial moisture content ranging from 29.3 to 31.0 percent wet basis and an average moisture content of 30.2 percent. The average retention time was 1.7 hours. The inlet BCFM ranged from 0.2 to 1.8 percent; the test weight from 50.6 to 54.0 pound/bushel. The final moisture content varied from

Table 6.1.3.2. Operating conditions during drying of corn in Test No. 1 of the M&W 450R dryer.

Grain Parameters	
Average inlet MC, % w.b.	31.3
Average outlet MC, % w.b.	20.0
Average inlet grain temperature, °F	36
Average outlet grain temperature, °F	42
Average inlet BCFM, %	1.2
Average test weight in, pound/bushel	48.4
Average test weight out, pound/bushel	49.4
Wet weight corn, pound	166,956
Initial breakage[1], %	26.7
Air Parameters	
Average drying temperature, °F	282
Average ambient dry bulb temperature, °F	32
Average ambient relative humidity, %	75
Airflow rates	
Heat section, cfm/bushel	73
Cool section, cfm/bushel	57
Static pressure	
Heat section, in. of w.c.	8.4
Cool section, in. of w.c.	7.6
Energy Use	
Fans and augers, kWh/hour	60.
LP gas, gallons/hour	44.3
Performance Data	
Temperature rise through recycle, ΔT °F	59
Test duration, hour	9.6
Average MC decrease, % w.b.	11.3
Average retention time, hour	1.4
Capacity, wet bushel/hour	359
Capacity, dry bushel/hour	302
Capacity, wet bushel/hour at 56 pound	310
Capacity, dry bushel/hour at 56 pound	266
Energy efficiency excl. elect., BTU/pound of water	1656
Energy efficiency incl. elect., BTU/pound of water	1740
Breakage susceptibility increase[1], %	9.6
Energy cost[2], ¢/bushel-point	.86

1. Breakage test determined at average MC of 9.32% w.b.
2. Based on 8.55 ¢/kWh, $6.15/10^6 BTU, and 56 pound/bushel.

Table 6.1.3.3. Operating conditions during drying of corn in Test No. 2 of the M&W 450R dryer.

Grain Parameters	
Average inlet MC, % w.b.	30.2
Average outlet MC, % w.b.	17.7
Average inlet grain temperature, ^{o}F	69
Average outlet grain temperature, ^{o}F	75
Average inlet BCFM, %	0.9
Average test weight in, pound/bushel	52.3
Average test weight out, pound/bushel	52.7
Wet weight corn, pound	263,146
Initial breakage[1], %	16.5
Air Parameters	
Average drying temperature, ^{o}F	263
Average ambient dry bulb temperature, ^{o}F	65
Average ambient relative humidity, %	90
Airflow rates	
Heat section, cfm/bushel	73
Cool section, cfm/bushel	57
Static pressure	
Heat section, in. of w.c.	8.0
Cool section, in. of w.c.	7.2
Energy Use	
Fans and augers, kWh/hour	60.
LP gas, gallons/hour	35.6
Performance Data	
Temperature rise through recycle, ΔT ^{o}F	55
Test duration, hour	16.9
Average MC decrease, % w.b.	12.4
Average retention time, hour	1.7
Capacity, wet bushel/hour	298
Capacity, dry bushel/hour	251
Capacity, wet bushel/hour at 56 pound	278
Capacity, dry bushel/hour at 56 pound	236
Energy efficiency excl. elect., BTU/pound of water	1383
Energy efficiency incl. elect., BTU/pound of water	1470
Breakage susceptibility increase[1], %	12.1
Energy cost[2], ¢/bushel-point	.73

1. Breakage test determined at average MC of 10.2% w.b.
2. Based on 8.55 ¢/kWh, $6.15/$10^6$ BTU, and 56 pound/bushel.

17.0 to 18.5 percent, with an average of 17.7 percent.

The grain flow rate in Test 2 was 2.9 feet/hour which translates to a wet bushel capacity of 298 bushel/hour assuming an average test weight of 52.3 pound/bushel. At the standard 56 pound/bushel test weight, a capacity of 278 bushel/hour is measured. The dry bulb temperature varied from 57 to 73^{O}F; the average relative humidity was 90 percent. Drying air temperature was an average 263^{O}F. The average inlet grain temperature was 69^{O}F; the outlet grain temperature 75^{O}F.

A total of about 40,000 pounds of water was evaporated in Test 2 in 16.9 hours from an average of 30.2 to an average of 17.7 percent. The L.P. gas used in the process was 600 gallon. The energy efficiency (excluding electricity) was 1383 BTU/pound of water. Fuel consumption was 35.6 gallon/hour.

The grain quality deterioration in Test 2 during the drying process resulted in a breakage susceptibility increase of 12.1 percent. [Moisture at the Wisconsin breakage test determination was an average 10.2 percent, wet basis].

The energy cost in Test 2 in terms of cents per bushel per percentage point moisture removed was 0.73 (¢/bu-pnt). This figure is based on the prevailing ambient conditions, the average moisture decrease, and the grain temperatures at the time of Test 3, and on electrical and LP gas energy costs of 8.55 ¢/kWh and \$6.15/10^{6} BTU, respectively.

Note that the temperature of the mixture of ambient and recycled air was 55^{O}F above ambient. In a conventional dryer the drying air would have been heated from 65^{O}F to 263^{O}F (a ΔT of 198^{O}F); in the 450R the temperature rise was from 120^{O}F to 263 (a ΔT of 143^{O}F). Thus a savings of about 28% in fossil fuel resulted assuming the moisture removal rate was not affected.

In Test 2 the temperature distribution of the inlet drying air and outlet exhaust air at various duct locations in the 450R dryer is shown in Table 6.1.3.4. Note that approximately a 36^{o}F temperature difference exists in the heating ducts; the minimum temperature was 248^{o}F, the maximum 284^{o}F. The exhaust air temperatures are very uniform.

Table 6.1.3.4. Temperature distribution in Test No. 2 of inlet drying air and outlet exhaust air at various duct locations in the M&W 450R dryer.

Location*	Inlet Air (^{o}F)	Exhaust Air (^{o}F)
1	248	
2	284	
3	256	
4		136, 140, 139
5	65	91, 91, 92

*Location 1 Heated air duct #1 (see Figure 4.3.1).
Location 2 Heated air duct #3
Location 3 Heated air duct #5
Location 4 Heated air exhaust duct #7, #12, #18
Location 5 Cooling air exhaust duct #7, #12, #18

6.1.4 Dryer Comparison

The two major criteria used in the comparison are:
(1) energy efficiency, and (2) grain breakage susceptibility.

The energy efficiencies were obtained by measuring the fuel and electricity usage in the drying process; the grain quality was measured in terms of increase in grain breakage susceptibility.

The experimental energy efficiency, and breakage susceptibility data are summarized in Table 6.1.4.1. In interpreting the data in Table 6.1.4.1, it should be remembered that the drying conditions were different under which the three dryers operated. This is true for the corn moistures (inlet and outlet), the drying air temperatures, and the ambient conditions. The effect of these parameters on dryer performance is quantified by simulation in the case of one of the dryers (i.e. the Zimmerman ATP 5000) in Section 6.3.

Table 6.1.4.1. Experimental energy efficiency and grain breakage susceptibility of three commercial grain dryers.

Dryer	Energy Efficiency (BTU/lb)	Breakage Susceptibility Increase, (%)	Final MC Range, (%)
Zimmerman[3] ATP 500	1985	6.5[1] - 15.9[2]	14.9 - 18.5
Meyer Morton[4] 850 Modified	1772 - 2124	22.6[2] - 27.1[1]	11.2 - 14.2
M&W[5] 450 R	1470 - 1740	9.6[1] - 12.1[2]	17.7 - 20.0

[1] MC at the breakage test determination was 9.3%, w.b.

[2] MC at the breakage test determination was 10.2%, w.b.

[3] Data from Table 6.1.1.2.

[4] Data from Tables 6.1.2.2 - 6.1.2.4.

[5] Data from Tables 6.1.3.2 - 6.1.3.3.

Certain general conclusions can be drawn from Table 6.1.4.1:

1. Concurrent flow drying is more energy efficient than crossflow drying; a 17 to 20 percent improvement in energy efficiency results when drying with the concurrent flow dryer compared to the crossflow dryer.
2. Increasing drying exhaust air recirculation in a crossflow dryer results in an energy savings of 15-20 percent.
3. Concurrent flow drying produces better quality corn than crossflow drying; a 25 to 45 percent reduction in breakage susceptibility occurs when dried in the concurrent flow dryer rather than the crossflow dryers.

6.2 Simulation Results of Zimmerman ATP 5000

The simulated results for the Zimmerman ATP-5000 are compared with the experimental data of Test No. 2 in Table 6.2.1. Excellent agreement exists between the experimental and simulated outlet moisture content (14.9% versus 15.1%). The simulated energy efficiency is 1909 BTU per pound of water removed versus 1934 BTU/lb for the experimental value. The predicted static pressures and outlet grain temperature do not agree as well with the experimental values. The values are computed using Shedd's (1953) data developed for lower airflows and assuming zero percent fines.

Table 6.2.1. Experimental and simulated results for the Zimmerman ATP 5000 dryer.

Dryer Parameter	Experimental	Simulated
Drying air temperature, ^{o}F	226	226
Airflow rates, cfm/bu		
Heat section	61	61
Cool section	127	127
Static pressure, in. of water		
Heat section	1.5	0.9
Cool section	1.7	2.6
Hybrid factor	--	0.9978
Grain flow rate, bu/hr-ft^2	35	35
Column width, in.	12	12
Length drying stage, ft	66.8	66.8
Length cooling stage, ft	18.6	18.6
MC in, % w.b.	25.1	25.1
MC out,% w.b.	14.9	15.1
Grain temperature out, ^{o}F	63	52
Energy efficiency, BTU/lb	1934	1909
Dryer efficiency factor	--	1.013

6.3 Dryer Simulation

The Zimmerman ATP 5000 was modeled under standard conditions for five, ten, and fifteen points of moisture removal. The standard conditions were proposed by Bakker-Arkema et al. (1980) with respect to grain and ambient conditions (see Table 6.3.1).

6.3.1 Standard Conditions for Dryer Simulation

The standard conditions used to obtain the dryer performance of the Zimmerman ATP 5000 are listed in Table 6.3.1.1.

Table 6.3.1. Standard conditions for performance evaluation of automatic batch and continuous flow grain dryers, drying shelled corn (Bakker-Arkema et al., 1980).

Inlet corn moisture content, % w.b.	30.5 ± 1.5 25.5 ± 1.5 20.5 ± 1.5
Outlet corn moisture content, % w.b.	
Drying	15.5 ± 1.0
Dryeration	18.0 ± 1.0
Combination drying	22.5 ± 1.0
Ambient air temprature, ^oF	60 ± 15
Ambient relative humidity, %	60 ± 15
Atmospheric pressure, in. Hg	30 ± 0.1
Inlet BCFM, %	$\leq$ 3.0
Inlet corn temperature, ^oF	60 ± 15

Table 6.3.1.1. Standard conditions used to obtain dryer performance.

Reference bushel weight at 15.5 MC w.b., lb/bu	56
Inlet grain temperature, ^oF	60
Inlet ambient air temperature, ^oF	60
Ambient relative humidity, %	60
BCFM, %	3.0

6.3.2 Zimmerman ATP 5000

The simulated dryer of the Zimmerman ATP 5000 consists of four stages. The stage lengths were selected by the location of the grain exchanger and temperature distribution (approximately 40°F difference) in the drying stages. The input parameter values for the simulation model are listed in Table 6.3.2.1.

Table 6.3.2.1. Input length of drying stages in the simulation model for the Zimmerman ATP 5000 dryer.

Drying Stages	
Stage 1 length, ft	33.4
Stage 2 length, ft	11.1
Stage 3 length, ft	22.3
Cooling Stage	
Stage 4 length, ft	18.5

The effect of initial moisture content on the grain retention time, recirculation temperature, and airflow rates in the drying and cooling stages of the Zimmerman ATP 5000 under standard conditions are given in Table 6.3.2.2.

Tables 6.3.2.3 and 6.3.2.4 illustrate the effect of initial moisture content and the grain flow rate on the performance of the Zimmerman ATP 5000 operating under standard conditions with and without cooling air recirculation, respectively.

Table 6.3.2.2. The effect of initial moisture content on grain retention time, recirculation temperature, and airflow rate in the drying and cooling stages of the Zimmerman ATP 5000 operating under standard conditions.

Dryer Section	20.5% Initial MC (% w.b.)	25.5% Initial MC (% w.b.)	30.5% Initial MC (% w.b.)
Grain retention time (hr)	1.0	1.9	2.7
Recirculation temp (^{o}F)	122	99	89
Airflow in three drying stages (lb dry air/hr)	980,271	1,023,630	1,043,745
Airflow in cooling stage (lb dry air/hr)	536,673	536,673	536,673

The simulation results show that:

1. the moisture content gradient across the drying column varies from 1.6 to 2.4 percent (1.3 to 2.3 percent without recirculation) for 5 versus 15 points removal.
2. The grainflow rate (capacity) is greatly affected by the initial moisture content; comparing 15 versus 5 points removal results in a 63 percent reduction in capacity.
3. Increasing the moisture removal from 5 to 10 to 15 points de-decreases the dryer throughput by 53 and 37 percent, respectively.
4. The exhaust humidity ratio in the first stage is higher at higher initial moisture contents, resulting in more moisture exhausted at higher inlet moisture contents.

5. The exhaust air temperature in the second stage reflects the effect of the grain exchanger between the first and second stage (second stage temperatures are higher than the third stage).
6. The air recirculation temperature depends upon the grainflow rate (and thus, the initial moisture content) and is lower at lower grainflow rates.
7. The energy efficiency with air recirculation is not as clearly affected by the initial moisture content as the energy efficiency without recirculation; in the air-recycle dryer, an increased recirculation temperature results in a lower airflow rate (i.e. 980,271 lb air/hr at 5 points versus 1,043,745 lb air/hr at 15 points), thereby,offsetting the better efficiency generally found at the higher inlet moisture contents.
8. Increase in airflow rate increases energy consumption.
9. Increase in moisture content can increase energy consumption.
10. The dryer energy efficiency is greatly affected by the recirculation of the cooler air; a 40 percent reduction in energy efficiency occurs when removing 5 points; a 20 percent reduction when removing 15 points.

In general, high initial moisture contents produce better efficiency as shown in the last row of Table 6.3.2.4 (2,681 versus 2,142) BTU/lb for the same airflow, however this trend in the Zimmerman ATP 5000 may not be true due to the grain retention time, recirculation temperature, and the airflow rate. High initial moisture content and low recirculation temperature have opposing affects on efficiency.

Table 6.3.2.3. The effect of initial moisture content (grainflow) rate) on the operation of the Zimmerman ATP 5000 operating under standard conditions and drying temperature of 226°F.

Parameter Values	20.5% (w.b.) Initial MC	25.5% (w.b.) Initial MC	30.5% (w.b.) Initial MC
MC Final (% w.b.) Min. / Ave. / Max.	14.5 15.5 16.1	14.3 15.6 16.2	13.8 15.4 16.2
Grainflow Rate (Bu/hr - ft^2)	68.0	37.0	25.5
Grain Retention Time (hr)	1.0	1.9	2.7
Average Air Exhaust Humidity Ratio (lb/lb)	.0211[1] .0249[2] .0222[3] .0083[4]	.0263[1] .0241[2] .0211[3] .0072[4]	.0298[1] .0242[2] .0203[3] .0068[4]
Average Exhaust Air Temp (°F)	85[1] 196[2] 154[3] 149[4]	97[1] 181[2] 165[3] 114[4]	97[1] 172[2] 172[3] 99[4]
Recirculation Temp (°F)	122	99	89
Energy Efficiency (BTU/lb)	1586	1736	1716

[1]Drying Stage 1 [3]Drying Stage 3

[2]Drying Stage 2 [4]Cooling Stage 4

Table 6.3.2.4. The effect of initial moisture content (grainflow rate) on the operation of the Zimmerman ATP 5000 operating under standard conditions without cooling air recirculation; grain exchanger located between stages 1 and 2; drying temperature of 226°F.

Parameter Values		20.5% (w.b.) Initial MC	25.5% (w.b.) Initial MC	30.5% (w.b.) Initial MC
MC Final (% w.b.)	Min.	14.4	14.1	13.6
	Ave.	15.3	15.3	15.2
	Max.	15.7	15.8	15.9
Grainflow Rate (Bu/hr - ft^2)		68.0	37.0	25.5
Grain Retention Time (hr)		1.0	1.9	2.7
Average Air Exhaust Humidity Ratio (lb/lb)		.0209[1]	.0263[1]	.0299[1]
		.0235[2]	.0234[2]	.0238[2]
		.0210[3]	.0204[3]	.0200[3]
		.0083[4]	.0072[4]	.0067[4]
Average Exhaust Air Temp (°F)		90[1]	102[1]	100[1]
		196[2]	182[2]	175[2]
		161[3]	172[3]	177[3]
		152[4]	114[4]	99[4]
Recirculation Temp (°F)		60	60	60
Energy Efficiency (BTU/lb)		2681	2370	2142

[1]Drying Stage 1 [3]Drying Stage 3

[2]Drying Stage 2 [4]Cooling Stage 4

CHAPTER 7

SUMMARY

This study of grain dryers has focused on the evaluation, the comparison, and the simulation of one of the three continuous-flow corn dryers. The two major evaluation criteria were: (1) energy efficiency, and (2) grain breakage susceptibility.

Three drying systems were investigated: (1) an off-farm continuous flow crossflow dryer with cooling air recirculation and grain exchanger, (2) an on-farm/off-farm continuous flow crossflow dryer with drying/cooling air recirculation and grain tempering, and (3) an on-farm single-stage concurrent flow dryer with counterflow cooler.

The experimental data were obtained during the 1983 and 1984 fall harvesting seasons. The major conclusions to be drawn from these tests are:

1. Air recirculation of part of the drying air results in at least 15 percent improvement in energy efficiency in a crossflow dryer.
2. Concurrent flow drying produces better quality corn than crossflow drying; a 25 to 45 percent reduction in breakage susceptibility increase occurs when dried in the concurrent flow dryer rather than the crossflow dryers.
3. Concurrent flow drying is more energy efficient than the cross-

flow drying; a 17 to 20 percent improvement in energy efficiency results when drying with the concurrent flow dryer compared to the crossflow dryers.

However, it should be remembered that the drying conditions were different under which the three dryers operated.

The major conclusions drawn from the simulations of the on-farm/off farm crossflow dryer with air recirculation are:

1. The grainflow rate (dryer throughput) is greatly affected by the initial moisture content; a 63 percent reduction in throughput occurs when removing 15 rather than 5 percent of moisture.
2. The recirculation temperature depends upon the grainflow rate (and thus the initial moisture content), and is lower at the lower grainflow rates.
3. The energy consumption is not greatly affected by the initial moisture content.
4. Airflow rate and initial moisture content have opposing affects on the dryer energy consumption.
5. The dryer energy consumption is greatly affected by the recirculation of the cooler air; a 40 percent reduction in energy efficiency occurs when removing 5 points; a 20 percent reduction when removing 15 points.

CHAPTER 8

SUGGESTIONS FOR FUTURE STUDY

The volume of experimental data on three commercial dryers collected over two harvestng/drying seasons for this study was limited due to unfavorable weather conditions and limited wet grain availability. The logistics of data collection at a commercial grain drying installation is time-consuming and expensive. Still, it is recommended that additional experimental tests be conducted at the three dryer sites in order to more accurately quantify the findings of this thesis.

Further suggestions include:

1. To analyze with the dryer manufacturers of the three dryers the experimental and simulated results of this investigation for possible dryer design modifications.
2. To encourage the three dryer manufacturers to employ simulation as a tool for optimizing their dryer designs.
3. To develop an accurate grain breakage susceptibility increase model for use with the dryer performance simulation models.
4. To develop more accurate airflow rate and wet bulb thermometer instrumentation for use in dryer testing.
5. To extend the Shedd curve for corn static pressure data beyond the 60 cfm/ft^2 range.
6. To re-evaluate the MSU crossflow grain dryer model for its ability to predict the crossflow cooling of grain.

CHAPTER 9

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