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E SILVA, JUAREZ DE SOUSA

AN ENGINEERING-ECONOMIC COMPARISON OF FIVE DRYING TECHNIQUES FOR SHELLED CORN ON MICHIGAN FARMS

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AN ENGINEERING-ECONOMIC COMPARISON OF FIVE DRYING TECHNIQUES FOR SHELLED CORN ON MICHIGAN FARMS

By

Juarez de Sousa e Silva

A DISSERTATION

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ABSTRACT

AN ENGINEERING-ECONOMIC COMPARISON OF FIVE
DRYING TECHNIQUES FOR SHELLED CORN
ON MICHIGAN FARMS

By

Juarez de Sousa e Silva

At least 70% of the total corn production in Michigan was estimated to be dried in automatic batch or in-bin batch-type systems. At an initial moisture content of 26% and an after-drying value of 15.5%, approximately 3.6×10^{12} KJ or 14.4×10^{8} liters of liquid propane were required to dry the 1979 Michigan corn crop.

Previous research in other U.S. Corn Belt states had shown that in-bin counterflow, in-bin dryeration, natural-air, and low-temperature combination drying produce high-quality corn and can substantially reduce the drying energy requirement under favorable weather conditions. The objectives of this thesis were to study the feasibility of applying and economically comparing the above techniques with conventional batch drying under Michigan conditions.

Five steel bins of 85 m^3 capacity were erected at a farm in Bellaire, Michigan. The system was designed to test each technique and adequately handle the farm's corn production. Four storage bins were arranged in a rectangular pattern, so that each could be filled with an auger from a central point, with an automatic cross-flow

batch dryer discharging from that position. Two of the storage bins were used to dry corn as a combination system. The first had a centrifugal fan with a 3.7 Kw motor delivering $2 m^3/min/m^3$ of natural air through a 3.7 m bed. A fan delivering 1.6 $m^3/min/m^3$ with a 2.2 Kw motor and a 10 Kw electrical heater were connected to the low-temperature system. The third bin was fitted with a fan delivering 0.8 $m^3/min/m^3$ for the in-bin dryeration. To the fourth bin an airflow rate of 0.3 $m^3/min/m^3$ was applied to cool hot grain from the in-bin counterflow dryer.

The quality of the corn was greatly affected by the drying procedures. The batch and in-bin counterflow dryers resulted in dried corn with significantly more stress-cracks and higher breakage-test numbers than the other drying techniques.

The energy efficiency and drying capacity of the automatic batch dryer increased substantially when the corn was dried in the combination systems to 23% rather than to 15%. The energy efficiency improved from 7521 to 5750 KJ/Kg H_2O, and the drying capacity (excluding cooling time) from approximately 2.3 to 3.5 ton/hr. The two combination systems showed the best energy efficiency with 3227 and 3755 KJ/Kg H_2O, respectively, for the natural-air and low-temperature combination drying.

The lowest operating energy costs of $2.76 and $2.80/ton were observed in the in-bin counterflow and in-bin dryeration, respectively, whereas the low-temperature combination drying showed the highest cost ($5.40/ton).

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A computer program (TELPLAN 03) was used to determine the annual per-ton cost of the five systems. Total drying costs of \$13.02, \$14.34, \$15.09, \$15.82, and \$16.63/ton were observed for the in-bin dryeration, in-bin counterflow, natural-air, batch, and low-temperature systems, respectively.

Hukill's analysis for deep-bed drying was employed successfully to simulate the batch and in-bin counterflow dryers. Simulations results indicated that drying-air temperature has a strong effect on the drying cost and efficiency of the batch dryer, whereas drying temperatures higher than 72°C have no significant effect on the cost and efficiency of the in-bin counterflow dryer. However, increasing the drying temperature increases the dryer capacity of the in-bin counterflow substantially.

In Michigan, the potential annual energy savings of the alternative drying systems are on the order of 2.0×10^9 MJ or the equivalent of 7.5×10^7 liters of liquid propane. For Brazilian conditions, the simulation results indicate that an energy of 3988 and 8243 KJ/Kg H_2O will be required for the in-bin counterflow and batch dryer, respectively.

Approved F. W. Bakker-Arkema
Major Professor 5-31-80

Approved Richard H. Wilkinson 2 June 80
Department Chairman

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LIST OF SYMBOLS

c = Cooling rate of air passing through grain of uniform moisture content

C_p = Specific heat of dry air, BTU/lb_m °F (KJ/Kg °C)

D = Number of dimensionless depth units to the point where M is computed

D' = Number of dimensionless depth units to the point where M is computed (Barre et al., 1971 analysis)

H = Time of half response, hour

h = Latent heat of vaporization of moisture in the grain, BTU/lb (KJ/Kg)

K = drying constant per hour

M = Moisture content (db) of grain at a given time and location in the dryer, decimal

M_e = Equilibrium moisture content (db), decimal

M_o = Initial moisture content (db), decimal

MR = Moisture ratio, $(M - M_e)(M_o - M_e)$

m = Mass flow rate, lb/ft^2 min. (Kg/m^2 min)

P = Constant for any given set of drying conditions

T = Drying air temperature, °F (°C)

T_{abs} = Product temperature, °R (°K)

T_g = Temperature at which air is in equilibrium with the grain at its initial moisture content after the air has cooled along a wet bulb temperature line, °F (°C)

T_o = Air temperature entry of the grain, °F (°C)

W = Density of dry matter, lb ft^3 (Kg/m^3)

X = Kernel depth in the drying bed, ft. (m)

Y = Number of dimensionless time units

Y' = Number of dimensionless time units (Barre et al., 1971 analysis)

1. INTRODUCTION

The United States, the number-one food producer in the world, uses only 3% of the national petroleum consumption at the farm level (Stout et al., 1979). Each year, the United States produces approximately 222 million tons of feed, 66.2 million tons of food grains, and over 45 million tons of soybeans (USDA, 1977). To maintain this first position in food production, American farmers have been making large expenditures in energy from petroleum, electricity, or other sources. Because it is still profitable to do so, one United States farmer can produce enough food for more than 50 other individuals (CAST, 1977). However, with the continuing fuel supply limitations, rapidly increasing prices, and the lack of price projections, the profit margin in agricultural production is continuously decreasing. This dramatic situation urges American farmers to take a new look at production techniques and to consider seriously any operation to reduce costs and the uncertainty of future supplies. The Council for Agricultural Science and Technology (CAST, 1977) suggested the following farm operations to minimize energy costs and consumption in the near future:

1. reduce energy use for fertilizer applications and tillage;
2. substitute enterprises that consume less energy;

3. invest in alternate technologies that (a) substitute energy inputs and (b) reduce energy use (e.g., alternative grain-drying technologies);
4. invest in new technology that uses such energy sources as the sun, the wind, and biomass;
5. modify farm enterprises to make them more efficient for the natural environmental conditions; and/or
6. cease farming if the adjustments are too difficult.

Since drying accounts for more than 60% of the energy required for corn production (Bakker-Arkema et al., 1974), there is no sounder reason to consider investment in grain-drying technologies in a very short run, as stated in recommendation 3 above.

1.1 Michigan Corn Production and Energy Use

According to Fedewa and Pscodna (1978, 1979), in the production of corn for grain, Michigan ranked ninth in the United States in 1977 and 1978. The corn produced accounted for 3.0% of the total United States production in 1977 and 2.6% of the total in 1978. The shelled corn production in Michigan increased from 2.3 million tons in 1960 to 3.9 million tons in 1975. According to the Michigan Agricultural Crop Reporting Service, the predicted corn production for 1979 was about 5.5 million tons. From 1960 to 1975, the energy used for drying increased from 75.2×10^{10}KJ to 329.5×10^{10}KJ (Brook, 1977). This increase in energy consumption apparently resulted from the shift from an ear-corn to a shelled-corn harvesting system.

There are several reasons for harvesting the grain early, when its moisture content is still high, instead of letting it dry in the field. While in the field, the crop is subjected to stresses due to drying and rewetting by the ambient relative humidity and rain; it can also be contaminated by mold or damaged by insects. At lower moisture contents, harvest losses are higher due to grain shattering. Hence, if the crop is harvested at high moisture content, drying is required for safe storage. In some cases, by harvesting the crop early, it is possible to grow a second crop on the same field, with an increase in the annual production per acre.

As previously stated, more than 60% of the energy required to produce corn on the farm is used for artificial drying. In 1972, 65% of the Michigan corn was dried in some kind of heated-air drying system; the prevalent fuel types were propane and natural gas (Bakker-Arkema et al., 1974). In 1977, however, 74.9% of the Michigan corn was artificially dried; the prevalent fuel type was propane, which accounted for 90.3% of the total drying energy. The percentage of corn dried in Michigan from 1974 to 1977 is shown in Table 1, which also shows the status of corn drying in four other midwestern states in the United States.

1.2 How Corn Is Dried in Michigan

Application of energy to lower the moisture content of harvested corn in Michigan is without any doubt a necessary practice because of the characteristic weather conditions in the state. For example, the 1977 corn-harvesting season presented Michigan farmers with a unique difficulty. Because of the prolonged wet weather in the fall, part of the corn was left standing in the field. This corn was harvested the next spring, and, according to Fedewa and

Table 1.--The percentage of corn dried by different drying techniques in Michigan and some midwestern states.

State or Region	Dried Naturally in Field or During Storage[a]				Dried Artificially							
					On-Farm				Off-Farm			
	Year											
	1974	1975	1976	1977	1974	1975	1976	1977	1974	1975	1976	1977
Michigan			b				b				b	
Northern[c]		77.9		50.0		16.8		39.5		5.3		10.4
W. Central		98.6		77.3				4.4		1.4		18.3
Central		51.6		18.5		47.2		78.1		1.2		2.8
E. Central		43.3		35.6		47.4		56.7		9.3		7.7
Southwest		31.6		18.7		65.7		79.7		2.7		1.6
S. Central		42.1		25.9		55.2		72.6		2.7		1.5
Southeast		57.7		25.2		38.4		73.5		3.9		1.3
Total	40.2	45.3		25.1	57.0	51.0		72.5	2.8	3.7		2.4
Illinois	21.0	33.5	13.0		77.5	65.0	85.0		1.5	1.5	2.0	
Indiana	12.0	12.2	11.8	10.7	86.3	87.2	86.6	87.4	1.7	0.6	1.6	1.9
Iowa	37.5	30.6	29.3	23.8	60.2	68.4	68.9	68.6	2.3	1.0	1.8	2.1
Wisconsin	39.7	45.3	44.8		57.3	52.0	52.9		3.0	27.	2.3	

Source: Fedewa et al. (1978) and Keyon et al. (1976).

[a]Does not include corn stored in silos as high-moisture corn.

[b]Survey was not conducted for Michigan in 1976.

[c]Upper Peninsula, northwest, and northeast combined.

Pscodna (1978), this might possibly have caused the change in drying technique used, as shown in Table 2.

Table 2: Shelled corn dried artificially in Michigan, by dryer type.

Dryer Type	Year (%)		
	1974	1975	1977
Batch	38.3	48.1	50.0
Continuous flow	45.7	39.5	40.4
Bin	14.3	9.2	8.4
Natural air	1.7	3.2	0.5

Source: Fedewa et al. (1978).

It is estimated that at least 70% of the 5.5-million-ton Michigan corn crop is artificially dried (Bakker-Arkema et al., 1979), primarily in automatic batch dryers between 82° and 110°C and in-bin batch-type drying systems between 43° and 60°C. At an average harvest moisture content of 26% (wb) and an after-drying value of 15.5%, about 140 kg of water per ton of corn are removed in the drying process (Brooker et al., 1974). Assuming an average energy efficiency of 7,000 KJ/Kg in conventional on-farm high-temperature drying systems (e.g., batch and continuous-flow dryers), approximately $3.6\text{x}10^{12}$KJ or $15\text{x}10^{7}$ liters of liquid propane were required to dry the 1979 Michigan corn crop; this is equivalent to $18,280,000 at current prices.

1.3 Objectives

The overall objective of this on-farm-type research is to conduct and compare, at the production level, five techniques for drying shelled corn on Michigan farms. The five drying techniques are (a) batch drying, (b) high/low-temperature drying, (c) high-temperature/natural-air drying, (d) in-bin counterflow drying, and (e) in-bin dryeration.

The specific objectives required to achieve the overall objective are as follows:

1. to demonstrate the technical feasibility of the high/low-temperature, high-temperature/natural air, in-bin counterflow, and in-bin dryeration drying systems in Michigan;

2. to demonstrate to the Michigan agricultural community that the present energy requirements for corn drying on the farm can be reduced by as much as 40% by applying one of these alternative drying methods instead of conventional high-temperature batch drying;

3. to study the economic aspects of the systems;

4. to study safety implications with respect to operation and product quality;

5. to use the Hukill (1954) analysis to describe in-bin counterflow drying and to predict the time required for drying; and

6. to study the effects that various drying parameters have on the capacity, efficiency, and energy cost of in-bin counterflow and batch-drying systems.

2. GRAIN DRYING AND STORAGE IN BRAZIL

Brazil, a republic of South America and the fifth largest country in the world, occupying 3,287,303 square miles and having more than 100 million inhabitants, is basically an agrarian country. Until a few years ago, it was considered to have one of the lowest production levels of grain/acre in the world, but this situation is rapidly changing. Brazil is now one of the world's foremost countries in agricultural production. In addition to producing more than 50% of the world's coffee, Brazil ranks first in sugar cane and cocoa production and second in soybeans. Ranking third in corn production worldwide, Brazil achieved in 1980 its record production of approximately 21 million tons (Veja No. 603, 1980).

Unfortunately, even though corn production substantially increased from 16 million tons in 1975 (IBGE, 1978) to an estimated 21 million tons in 1980, provision of the necessary storage and drying facilities has not been well planned. In many regions of Brazil (based on the writer's experience), storage facilities under normal conditions are inadequate in quantity and quality. For example, during the 1980 harvesting season the territory of Rondonia faced a serious problem. With an estimated 276,000-ton production, harvested at a high initial moisture content and with no transportation available, only a 60,000-ton storage capacity was provided. Also, in the region of Alta Floresta in the state of

Mato Grosso do Sul, collapse of the fuel supply caused heavy losses in rice production and an increased transportation cost (Veja No. 601, 1980). Under conditions of stress, such as dramatic increases in production, the status of the current grain drying and storage situation in Brazil is brought into sharp focus.

2.1 The Need for Drying and Storage in Brazil

In 1980, an estimated 46 million tons of cereal grain (wheat, rice, soybeans, and corn) were produced in Brazil (Veja No. 603, 1980). This figure does not include grain sorghum, beans, and coffee. The fact that these crops are seasonal and harvested at certain times of the year necessitates holding them for varying lengths of time to provide consumers with as uniform a grain supply as possible. In the northern and northeastern parts of Brazil, where agriculture (excluding sugar cane, rice, and cocoa) is primarily at the subsistence level, or where the grain is used for animal feed, farm drying and/or storage is a necessity. In those regions, only a small portion of the cereal grain is marketed; however, storage for that which is marketed must be provided, mainly in urban centers. Storage in urban centers in the northern and northeastern regions is also a necessity because the major source for urban-population supplies is from the southern states, and the commodities must be kept in good condition until they are delivered to the consumers.

2.2 The Storage Environment, Education, and Technology

It is not difficult to document the need for grain drying and storage in Brazil, which comprises 60% of the South American continent (approximately the size of the United States). However, providing storage and technology capable of preserving the quality of cereal grains in the various regions of the country is a more complex undertaking. Much of Brazil is characterized by climates that are not conducive to the safe storage of grain. High temperatures and relative humidities exist over prolonged periods of time, making the potential for deterioration due to insects, molds, and rodents extremely high. Even with the best of facilities, storing grain under tropical conditions is a difficult task.

In many situations the individuals responsible for storing grain in Brazil are not completely aware of the hazards involved in storing the product. Most of them may be aware of the possibility of physical losses due to insects, rodents, and molds. However, only a few are concerned with contamination in the form of urine, excrement, hair, and toxins that occurs as a result of insect, rodent, and mold infestation. With only a few exceptions, the biochemical changes that occur, reducing the nutritional quality of the grain as food for humans and animals, are completely ignored. The manner in which grain is managed or maintained in storage (mainly at the farm level) reflects the lack of technological knowledge of the individuals responsible for the storage facilities. Besides the loss in market quality, large quantities of grain are lost yearly because of improper storage techniques and/or facilities. Fortunately, the government is concerned about this situation and has invested in grain drying and storage education. The National Center for Storage Training (CENTREINAR), located on the campus of the Federal University of Viçosa, has recently been established. This institution, which has a number of specialists on its staff, has been given the responsibility of developing, adapting, and testing technology applicable to the Brazilian storage sector. CENTREINAR is also responsible for training individuals in grain drying and storage at different levels for the industrial, governmental, and private storage sectors.

2.2.1 Grain Storage Situations in Brazil, From Producer to Consumer

In recent years the Brazilian government has been spending a significant amount of money in an effort to eliminate bottlenecks and also to reduce transportation costs and losses in its storage and transportation systems. Because of the complexity of the "producer-consumer" path, the bottlenecks are very difficult to determine and are sometimes inevitable.

As grain flows from producer to consumer, a multitude of paths may be followed. Figure 1 illustrates the complexities that may be encountered in these paths. No two states appear to have the same marketing-pattern network. Whatever pathway grain takes from producer to consumer, it is inevitable that storage will take place at one or more points in this flow.

The simplest situation is one in which the producer holds grains on the farm for his own consumption. Quantities held on the farm generally range from 60 to 70% of the total production. Of course, there are many exceptions; for instance, all of a farmer's production may be sold to mills at harvest time and bought back as needed. However, the major portion of grain produced in Brazil is

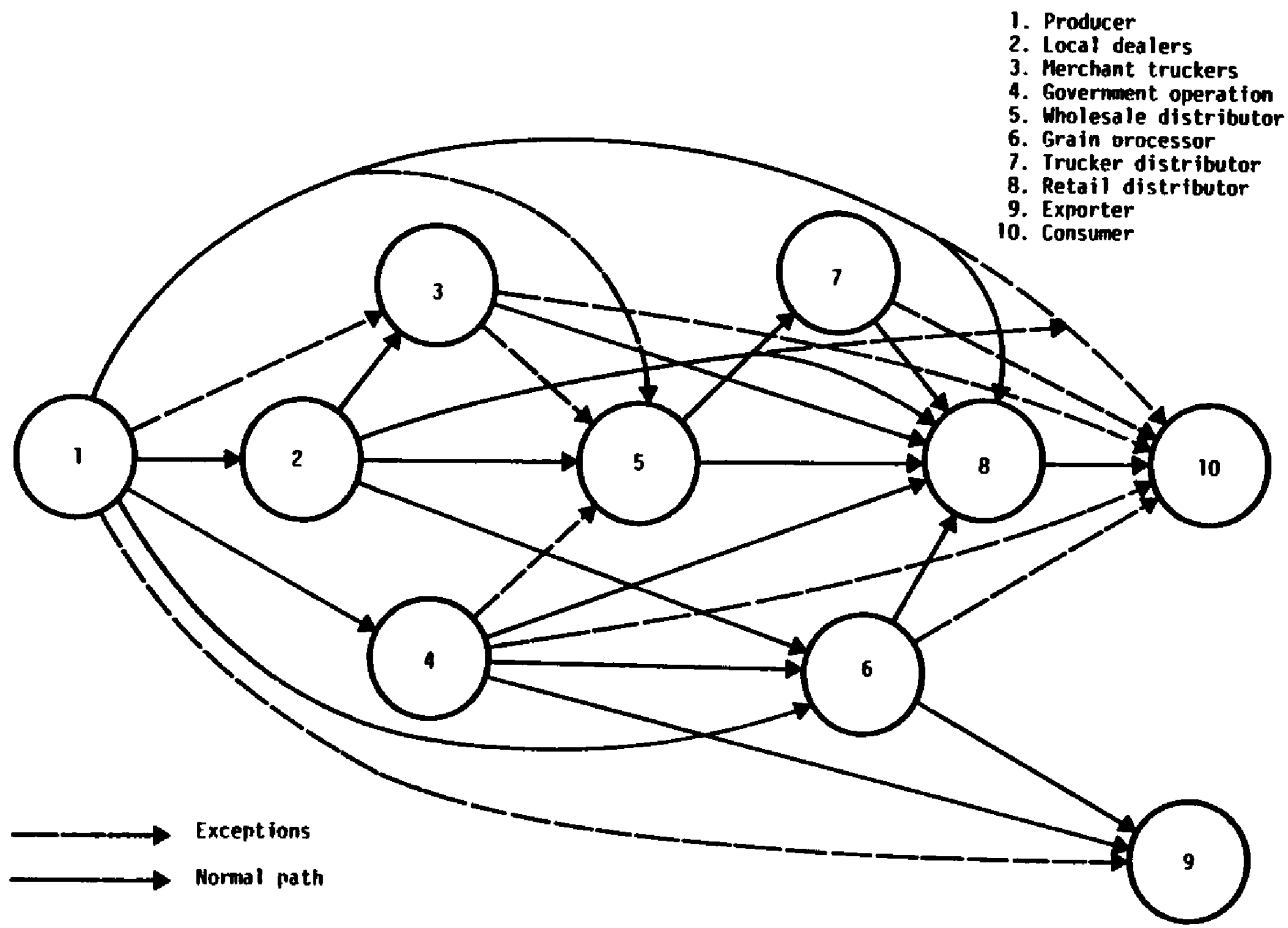


Figure 1.--Grain-flow pattern in Brazil.

stored on farms. Since the bulk of the country's cereal food supply is stored on the farm for at least 60 days, it seems ironic that improvement of this level of storage has not yet received the necessary consideration or emphasis.

Various types of farm-storage facilities are used in Brazil. They vary from discarded oil drums to modern silos. With some exceptions in the southern states, farm storage in Brazil, at best, leaves grain supplies vulnerable to insect and bird depredation and, in areas where high temperatures and humidity exist, to deterioration due to molds. Fortunately, in recent years the Brazilian government has been seeking a way to improve farm storage. Some studies have been conducted, mainly by the Federal University of Viçosa, where an economic and physical study of on-farm storage in various regions of Brazil was undertaken (UREMG, 1968).

With some exceptions, most of the facilities used at the urban level do not vary significantly from those used on the farm. The urban-level storage referred to here is that maintained by local dealers in small cities. Grain is held in bags and stored in various types of structures, usually shops or storage rooms. Security from insect, rodent, and bird attack is usually comparable to that on farms.

Cooperative effort on the part of farmers in the southern states has resulted in the development of improved community-level storage facilities. Fortunately, this form of cooperation is becoming quite common.

Urban-level storage can form the first link in the movement of grain off the farm into major marketing channels. Lack of development of these "first collection points" in the flow of grain from producer to consumer has been one of the major factors hindering the success of some grain-stabilization programs. The existence of inadequate storage facilities at the urban level is not the main drawback, but rather the lack of an adequately developed marketing system (transportation facilities, grading systems, and market news). The weakness of this link in the overall flow of grain from producer to consumer is partially responsible for large storage facilities being empty or not fully used.

In most parts of Brazil, the urban sector of the grain trade uses warehouses of various types of construction to store bagged grain. Some processors are developing bulk storage at their facilities; however, most of the grain at the processor level is stored in bags because grain is handled in bags throughout the marketing system.

The quality of storage at private and commercial central storage facilities ranges from very poor to excellent and depends, in part, on the level of knowledge possessed by those responsible for the grain.

2.2.2 Governmental Storage Operation

In most governmental operations, storage facilities are used in support of grain purchasing, stabilization, and/or reserve programs. In general, storage facilities range from small, simple warehouses to elaborate, large-bulk-handling silos. The larger storage facilities are generally located in the major consumption centers and at port locations. Smaller facilities are usually located at minor consumption centers and are used either for collecting grains or for distributing them to the population.

One of the major problems is determining where storage facilities should be located and what types and how many should be built. In many parts of Brazil, large facilities stand idle or are underused; hence planning and implementation of storage programs have not been completely successful.

In general, improvement is needed in the movement of grains from the producer to the consumer (farm, urban, commercial, processor, and government storage). To summarize, problems encountered in storing grains safely in Brazil are of a biological, economical, and political nature. There is a lack of knowledge of the factors causing grain deterioration and proper "management."

Note: The writer drew from his own experience in writing this chapter. Therefore, only two references were cited.

3. LITERATURE REVIEW

Grain and seeds are both exceedingly durable and highly perishable. If they are harvested soundly and are subsequently kept at low moisture content and low temperature, they may retain their original germinability and other qualities for a long period of time. Based on this information, the following literature review was developed.

3.1 Necessity of Grain Drying

The objective of proper grain storage is to maintain throughout the storage period the biological, chemical, and physical characteristics that the grain possessed immediately following harvesting. The drying operation, which will be of concern in this study, is an inherent part of the storage process. According to Brooker et al. (1974), the quality of grain cannot be improved during storage. Improperly harvested grain will remain of low quality no matter how well it is stored. High harvest moisture content and improper harvesting (high cylinder speed) are the most important factors affecting the quality of the grain and, of course, its storability.

The principal causes of loss in quality and quantity of stored grains and seeds are rodents, insects, mites, birds, and fungi. Respiration may, to a lesser extent, contribute to a loss of dry matter during grain storage, although the losses due to respiration are minor compared to those resulting from the causes previously mentioned (Brooker et al., 1974).

In 1968, according to studies conducted by the Federal University of Vicosa and supported by the National Bank of the Development, the amount of grain lost by on-farm storage in Brazil, the third largest corn producer in the world (Schmidt, 1978), was estimated at 35% (UREMG, 1968). In the United States, losses from grain pests are not as large as in some parts of Brazil, where climatic conditions and facilities for handling and storing of grains are less favorable. Nevertheless, losses do occur in the United States, and the cost of prevention and control, according to Cotton (1963), was estimated to be about $400 million annually in 1962.

The means of controlling rodents, insects, mites, and birds are known, and they are being effectively applied, as indicated by the low degree of infestation in grain stored in the United States and Canada. The same is not true for fungi-type spoilage, which only a few decades ago was recognized as a more important cause of spoilage. The major types of losses caused by mold growth in stored grains are: (a) degrease in germinability, (b) discoloration of part or all of the seed kernel, (c) various biochemical changes, (d) production of toxins that may be injurious if consumed by man or animals, and (e) loss in weight.

The major conditions that influence the development of storage fungi in stored grain are: (a) grain moisture content, (b) grain temperature, (c) storage time, (d) degree of field fungi infestation, (e) foreign material present, and (f) insect and mite activities.

High moisture content is the single most important contributor to mold growth. In reality, fungi are not directly affected by moisture content; they are actuated by relative humidity (Christensen & Kaufmann, 1974).

Warm temperatures are also conducive to mold growth. Molds grow most rapidly at temperatures between 10° and 35°C and at high relative humidity (Brooker et al., 1974). Prolonged growth of fungi on moist grain at temperatures in the range of 1.7° to 7.2°C may result in the formation of mycotoxins (USDA, 1968).

During harvesting, the kernels are subjected to mechanical impacts, which cause stress-cracks and breakage resulting in "open doors" to organism invasion (Brooker et al., 1974). Along with mold development, under unfavorable harvesting and storage conditions the grain moisture content may be high enough to permit heating and other types of damage such as discoloration, loss of viability, increase in fatty acidity, and deterioration in nutritive qualities (Christensen & Kaufmann, 1969).

According to Copeland (1976), the increase in fatty acidity in seeds is largely due to invasion by fungi and is a major symptom of seed deterioration at moisture content about 14%.

The respiration process involves release of energy by oxidation of carbohydrates and other organic nutrients. Carbohydrate is the major substance in seeds and especially in corn. Respiration is represented by the following equation:

$$C_6H_2O_6 + 6\ O_2 \rightarrow 6\ H_2O + 6\ CO_2 + 677\ \text{cal}$$

When respiration proceeds rapidly and produces heat more quickly than it can be dissipated, the temperature of the grain rises and mold growth is more likely.

Although ignored in the past as a cause of heating in stored grain, microorganism activities are now generally recognized as a major cause for heating. According to Christensen and Kaufmann (1969), most or all heating up to 21-24°C is caused by microorganisms. The growth of fungi decreases at relative humidities below 70% and temperatures below 0°C. Thus it is essential to dry the product at a safe moisture-content level and maintain the product at this moisture level during storage. The 12.5-13.5% moisture-content range is generally accepted to be the ideal range for long-term storage of corn (Brooker et al., 1974).

3.2 Drying Procedures for Different Uses of Corn

The amount of moisture content in grain has a definite effect on its characteristics during harvesting, storing, germinating, and milling. For such processes, there is an optimum or critical moisture content above or below which the results are not satisfactory.

Agricultural materials must be dried by different procedures because of the inherent characteristics with respect to the following factors:

1. Temperature tolerance. High temperatures may reduce germination, partially cook a product, or change its chemical or physical characteristics.

2. Humidity response. Grains that undergo physiological or other changes during drying have to be dried with air of a specific humidity. For example, if soybeans are to be used for seed, the relative humidity of the drying air must be kept above 40% regardless of the drying-air temperature; below 40% relative humidity, severe cracking damage can occur if the air temperature is too high (Dalpasquale, 1979).

3.2.1 Drying Grain for Animal Feed

Even though corn is not the most important human food source, it is by far the most important one for animal agriculture. Corn constitutes the largest proportion of most mixed feeds, often making up 50-70% of the total formula. This has a great effect on cost and quality of the finished feed. It is estimated that the total volume used as animal feed both in farm use and in commercial rations in the United States is about 85% of the domestic usage (Stewart, 1978).

The effect of drying temperature on the nutritional value of corn as an animal feed has received considerable research attention. Hathaway et al. (1952) found that corn dried at temperatures above 60°C significantly decreased as a source of energy and also decreased in palatability. Sullivan et al. (1975) reported that heat has a definite effect on the nutritional value of corn but that the decrease in commercial quality due to drying at an elevated temperature may not correspond to a decreased value of corn as animal feed.

Jensen et al. (1960) reported that drying temperatures of 60°, 82.2°, and 104°C have no deleterious effects on the nutritive value of corn for swine, as measured by growth rate and feed use. Gansmann et al. (1952) found only minor effects on the niacin, pantothenic acid, riboflavin, and pyridoxine content of corn dried at 43.3°, 48.8°, and 82.2°C. However, Jensen et al. (1960) found that when pigs had free access to roller-ground corn, the percentage of selection of the 60°, 82.2°, and 104°C corn samples was 73.5%, 25.0%, and 1.5%, respectively.

In a more recent study, Jensen (1978) showed that by roasting corn at 14% and 23% moisture, lysine availability was reduced at 150°C and at 127°C. He found that niacin was unaffected by roasting temperature, but pyridoxine availability was significantly reduced in 14%-moisture corn when it was dried at 160°C.

Although investigators may disagree about nutritional changes due to high-temperature drying, they do agree that physical and chemical characteristics such as consistency, energy content, palatability, harness, color, moisture, and protein and amino acid profile are affected by drying temperature (Williamson, 1975).

3.2.2 Drying Corn for Milling

Although farmers and elevator operators who are drying corn often consider only its feed characteristics, corn millers are seriously concerned about the increased volume of artificially dried corn coming into the market (Freeman, 1978; Rutledge, 1978). In 1974, for example, over 7.6 million tons of corn were sold for industrial purposes (Anon, 1975).

According to MacMasters et al. (1959), improper drying affects the grain protein and starch content, thereby creating problems such as: (a) loss of starch in by-products because of incompleteness and difficulty in grinding, and (b) poor separation of starch and protein in the centrifuges, resulting in a low recovery and poor quality of the recovered starch.

Among other problems, difficulty in drying the corn gluten fraction, poor germ separation, low yield of oil from germ, and high fatty acid content of the oil are frequently cited. Freeman (1978) reported that corn dried from 30% to 15% moisture in a single pass had a 25% lower production capacity, poor dewatering of coarse fiber, increased starch in gluten with a correspondingly lower starch yield per bushel of corn, higher protein content of isolated starch, and lower starch viscosity.

According to MacMasters (1959), the difficulties of processing artificially dried corn are so great that some corn wet-millers refuse to purchase corn known or suspected to have been dried at high temperatures.

Watson and Hirata (1962) concluded that since kernel viability is evidently more easily altered by drying conditions than are other properties examined, corn dried to preserve viability should invariably be suited for starch manufacture. The drying temperature should not exceed 71°C.

3.2.3 Drying Grain for Seed

In general, the techniques used to dry seeds do not differ greatly from those used to dry grain for other purposes such as for feed or milling. However, a high degree of germination must be preserved, and according to Copeland (1976), extra care must be taken in dryer selection, control, and management. The drying operation can be injurious to seed in different ways. It has been well established that drying-air temperatures higher than 38°C are detrimental to seed quality. Copeland (1976) stated that the higher limit varies with the type of seed; he established 38°C as a safe limit. Wileman and Ullstrup (cited in Hukill, 1954) showed that drying temperatures up to 49°C can be used with corn of 25% moisture content or less, but above 25% the drying temperature should not exceed the 38°C limit. The rate of moisture removal is also an important factor; excessive drying rates may cause stress-cracks. Overdried seeds are also susceptible to mechanical damage, which is also detrimental to seed quality (Copeland, 1976).

3.3 Commercial Corn Quality as Affected by Drying Procedures

Discussed in the previous section of the literature review were some of the effects of artificial drying of corn on its composition, nutritional value, viability as seed, and industrial-processing characteristics. However, the above qualities are not taken into account in determining the actual market grade.

Corn is classified into one of five official commercial grades in the United States on the basis of test weight, moisture content, proportion of broken corn and foreign material, and the proportion of damaged kernels. In this section, these factors and how they are affected by drying are reviewed.

3.3.1 Test Weight

The test weight of corn depends on a combination of true density of the kernel and its packing characteristics. The value of the test weight usually changes during the drying process. The amount of the change is a function of the initial and final moisture content, the drying temperature, grain variety, type and amount of impurity, and the degree of damage. Test weight is generally taken as an indicator of grain quality. Freeman (1978) stated that low test weight per se reduces the value of corn for wet milling, regardless of the reason for low test weight.

Hill (1975) reported that milling trials showed no significant difference in yield and quality of the final product between corn of high and low test weights, and that no research had been published to indicate a correlation between test weight and quality of the product. According to Stewart (1978), test weight within normal ranges (over 50 lb./bu.) has not shown any correlation with the energy level or feeding value of corn.

Under normal conditions, the lower the moisture content, the higher the test weight. Overdrying the corn and using excessive temperature will damage the kernels and result in smaller test-weight increase. At the same final moisture content range, the higher the drying temperature, the lower the test weight, according to Shove (1978), Gustafson et al. (1978), and Peplinski et al. (1975).

3.3.2 Broken Corn

Despite the fact that drying per se does not directly affect the number of broken kernels, it is well known that grain is physically and physiologically damaged when dried at excessively high temperatures. This can be expected to increase the grain's susceptibility to handling damage.

One of the apparent types of physical damage due to high temperature is stress-carcking. Thompson and Foster (1963) defined stress-cracks as the fissures in the endosperm, or starchy inside of the kernel, in which the seed coat is not ruptured (see Figure 2). The results of Thompson and Foster (1963), in which they related the drying speed and amount of expected breakage, have been confirmed by various authors. Factors other than drying-air temperature and drying rate that are closely related to stress-crack formation are drying systems, initial moisture content, and cooling rate (Ross & White, 1972). These researchers also found that there is a general decrease in stress-cracking as the grain is dried to lower moisture contents and as drying is started at lower moisture contents.

Gustafson et al. (1978) concluded that the final moisture content for high-temperature drying above 18% does not appear to cause a significant increase in breakage susceptibility, but the product of heating time and change of moisture content appears to be the best predictor of change in breakage.

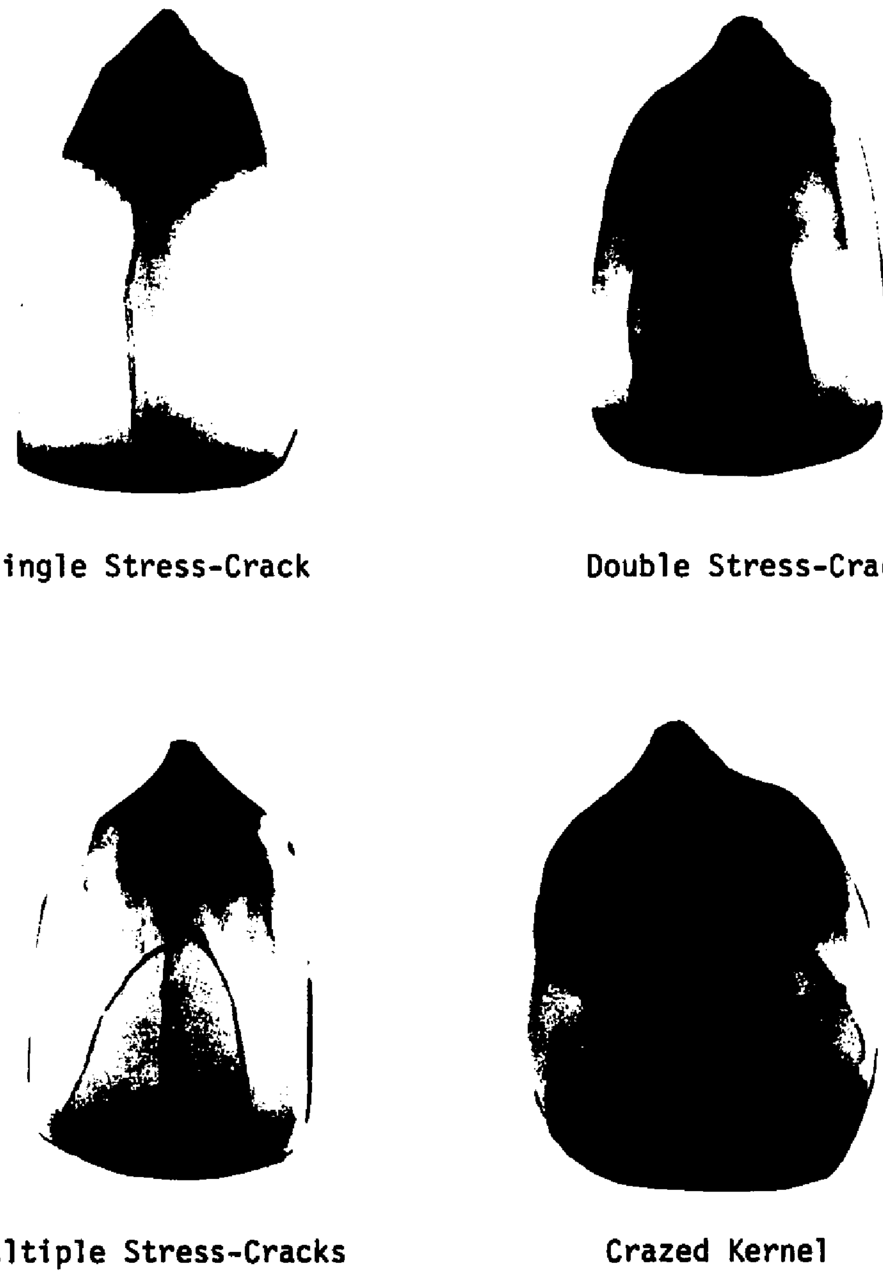


Figure 2. Types of stress-cracks in dried corn. (From Chowdhury & Kline, 1978.)

In the same final moisture range, Shove (1978) presented a table that clearly shows the difference in susceptibility to breakage (as indicated by the Stein Breakage Test) for corn dried with high temperatures and with natural air. Differences in breakage of up to 11.7% by weight were obtained.

Chowdhury and Kline (1978) stated that little information is available regarding the effect of harvesting and pre-harvesting conditions on the formation of stress-cracks in the corn kernel. According to these writers, Roberts (1972) reported an average of 25.8% damaged kernels (before artificial drying) due to stress-cracks.

Paulsen and Nave (1978) found that the percentage of kernels with no stress-cracks in three combine types ranged from 90% to 100%. They concluded that there was no significant variation in percentage of stress-cracks between cylinder- or rotor-type combines or among the various peripheral speeds.

Attempts have been made to develop a testing device that can predict the susceptibility of grain to mechanical damage. The designs are based on subjecting the corn samples to a predetermined loading or impact condition and evaluating the resultant damage. At present, only the Stein Breakage Test is used to provide a standard evaluation of the mechanical damage done to corn during harvesting, handling, and drying. The great variation in breakage susceptibility caused by test conditions such as moisture content and grain temperature is pointed out as being a major disadvantage in using the Stein Breakage Test.

3.4 Drying Systems

There are two basic methods of grain drying: high- and low-temperature methods. In the United States, high-temperature drying has been the primary technique for more than 25 years. Although this method requires only a short drying time, it also has very low energy efficiency, high fossil-fuel consumption, and low product quality. Low-temperature grain drying (with no heat or with low heat from electricity, liquid propane, solar energy, or any kind of heat source) is an energy-efficient process and results in a high-quality product when proper management is applied. The spoilage risk in warm and humid areas is the main problem encountered with low-temperature drying.

Brooker et al. (1978) subdivided the on-farm high- and low-temperature drying methods into the following categories:

1. high-speed, high-temperature batch and continuous-flow dryers;
2. continuous-flow in-bin drying systems;
3. batch-in-bin drying systems with and without grain stirring;
4. low-heat and no-heat in-bin drying systems with and without grain stirring; and
5. combination systems, in which high-speed batch or continuous-flow systems are combined with low-heat or no-heat in-bin drying systems.

The grain-drying techniques will be reviewed, based on the preceding classification.

3.4.1 Batch Dryers

A popular method used on small- to medium-sized farms in the United States is batch drying. Three common types of batch dryers are:

1. Batch-in-bin dryer, in which the air enters the grain through a perforated floor or a duct arrangement at the bottom of the bin and leaves through the top surface of the grain (Figure 3).

2. Batch dryer (Figure 4), in which air enters the grain from a cylindrical perforated central duct and leaves mainly through the perforated external wall.

3. Column-batch dryer, in which the air moves across or perpendicular to a stationary grain column (Figure 5).

In any batch dryer, the grain at the air intake side dries most rapidly; the grain on the exhaust side takes the longest to dry. The resultant grain-moisture-content gradient is pointed out as being one of the greatest disadvantages of batch drying. According to Brooker et al. (1974), the problem of moisture gradient is more accentuated in batch-in-bin dryers because of the possibility of insufficient grain mixing when the dryer is unloaded.

Among the wide variety of batch-drying methods (Brooker et al., 1974; Sutherland, 1975; Brooker et al., 1978), column-batch dryers are particularly popular because of their simple construction and operation and because their initial cost is generally lower than that of continuous-flow-type dryers.

According to Bakker-Arkema et al. (1978), column-batch dryers differ from batch-in-bin systems in the following ways: (a) the bed thickness is significantly less (.30-.46 cm), (b) the airflow is higher (greater than 40 $m^3/min/m^3$), (c) the air temperature is higher (up to 112°C), and (d) the moisture gradient across the grain column is less (3-5% wb).

Although column dryer designs have changed relatively little over the past decade, some innovative models are continually being marketed. (See, for example, Figure 6.) The energy efficiency of the design shown in Figure 6 is higher than that of conventional column-batch dryers. However, the fan must overcome the resistance of two columns of grain. Also, chaff and fines that filter through the cooling section will accumulate in the heating plenum. The system can not be used for dryeration.

The column-batch dryer has a number of design and operational parameters that can be adjusted to optimize dryer performance. Column height, length, and thickness can be varied to achieve the desired capacity. To achieve a particular final moisture content, the residence time will be a function of the initial moisture content, drying-air temperature, airflow rate, and, to a lesser degree, inlet grain temperature.

Kirk (1959), working with grain-column thicknesses of 10.2 20.3, 30.5, and 40.6 cm, made the following observations:

1. the 20.3, 30.5, and 40.6 cm columns are very similar in their drying-air requirement;

2. air requirements, and thus operating costs, are not materially increased with an increase of up to 5.08 cm of water for 20.3, 30.5, and 40.6 cm columns in static pressure;

3. despite the increase in drying capacity with an increase in static pressure, for a given drying-column area the 20.3, 30.5, and 40.6 cm columns are all closely grouped in their drying output, and the increase in capacity remains virtually linear with static pressures in the range of .63 to 5.1 cm of water.

In some batch dryers, the drying period can be divided into two parts: Ultra-high-temperature air (102-113°C) is provided during the first part of the cycle and lower-temperature air (79.4-83.3°C) during the second phase.

The following general statements can be made about column-batch and batch-in-bin dryers (Morey et al., 1976):

1. fuel and fan operation costs are reduced by decreasing the airflow rate at constant temperature or by increasing the drying-air temperature at a constant airflow rate;

2. moisture-content and grain-temperature gradients are reduced by increasing the airflow rate at constant air temperature or by decreasing the drying-air temperature at a constant airflow rate.

The capacity of a batch dryer is decreased by a reduction in air temperature or airflow rate. The capacity and efficiency are increased by increasing the column thickness or bed depth, although this design increases the grain-temperature and moisture-content gradients across the grain column or grain bed.

3.4.2 Continuous-Flow Dryers

Continuous-flow dryers are categorized by the relative direction of grain and air movement inside the drying chamber (Figure 7).

High-speed, high-temperature continuous-flow dryers (Figure 8) are normally used for high-volume operations. With the exception of the semi-continuous in-bin counterflow system, such dryers do not function as storage units. As stated by Brooker et al. (1978), the term "portable" is often applied to farm-type continuous-flow dryers. Portability in these units is only a factor in moving the unit from the factory or dealer to the farm location, and does not refer to their permanence.

When the grain and airflow are in the same direction in the drying chamber, the system is said to be a concurrent-flow dryer. This system has only recently become commercially available (Brooker et al., 1978). In concurrent-flow dryers the hottest air (149-260°C) encounters the wettest grain; this causes the air to cool rapidly because of the high rate of evaporation (Brook, 1977). The air and product temperatures versus grain depth are illustrated in Figure 9.

The advantages of a concurrent-flow over a cross-flow dryer are its lower energy usage, higher grain quality, lower pollution, and discharge of grain at a uniform moisture content (Brook, 1977; Brooker et al., 1978; Dalpasquale, 1979).

The in-bin continuous-flow dryers are classified as counter-flow dryers and will be discussed in detail later in the "Shivvers System" section.

3.4.3 Low-Heat and No-Heat In-Bin Storage Drying

Low-heat and no-heat (natural air) in-bin drying include such processes as layer drying, electric-heat drying, solar drying, and natural-air drying. According to Brooker et al. (1978), these techniques may or may not be associated with grain stirring (Figure 10).

Natural-air and low-temperature-air drying are similar processes (Bakker-Arkema et al., 1978). The difference is that no heat (except the approximately 1°C from the fan) is supplied to the intake air in the natural-air system, whereas low-temperature drying is accomplished with an additional 3-5.5°C (Shove, 1978) from propane combustion, electric heat, or another alternative heat source such as a solar collector, cob burner, or heat pump (Zink et al., 1978). Liquid propane gas and electric heat are the most widely used heat sources for low-temperature drying; both have the benefit of low capital investment. However, Brooker et al. (1978) asserted that liquid propane is usually not used because interval timers or other on-off control systems are needed to limit the total heat delivered.

The airflow rate required for a drying system design depends on the harvest date, harvest moisture content, and location. When operating at a specified airflow rate, drying performance is further dependent upon fan and heater management and on year-to-year variation in weather conditions (Pierce & Thompson, 1978). Table 3 contains simulated results and illustrates the minimum airflow depending on the initial-moisture content and harvesting data at different locations in the United States.

Natural-air and low-temperature drying do have limitations. Because of the low airflow rates and small or no amount of supplemental heat, it may take several weeks to dry a deep bin of grain.

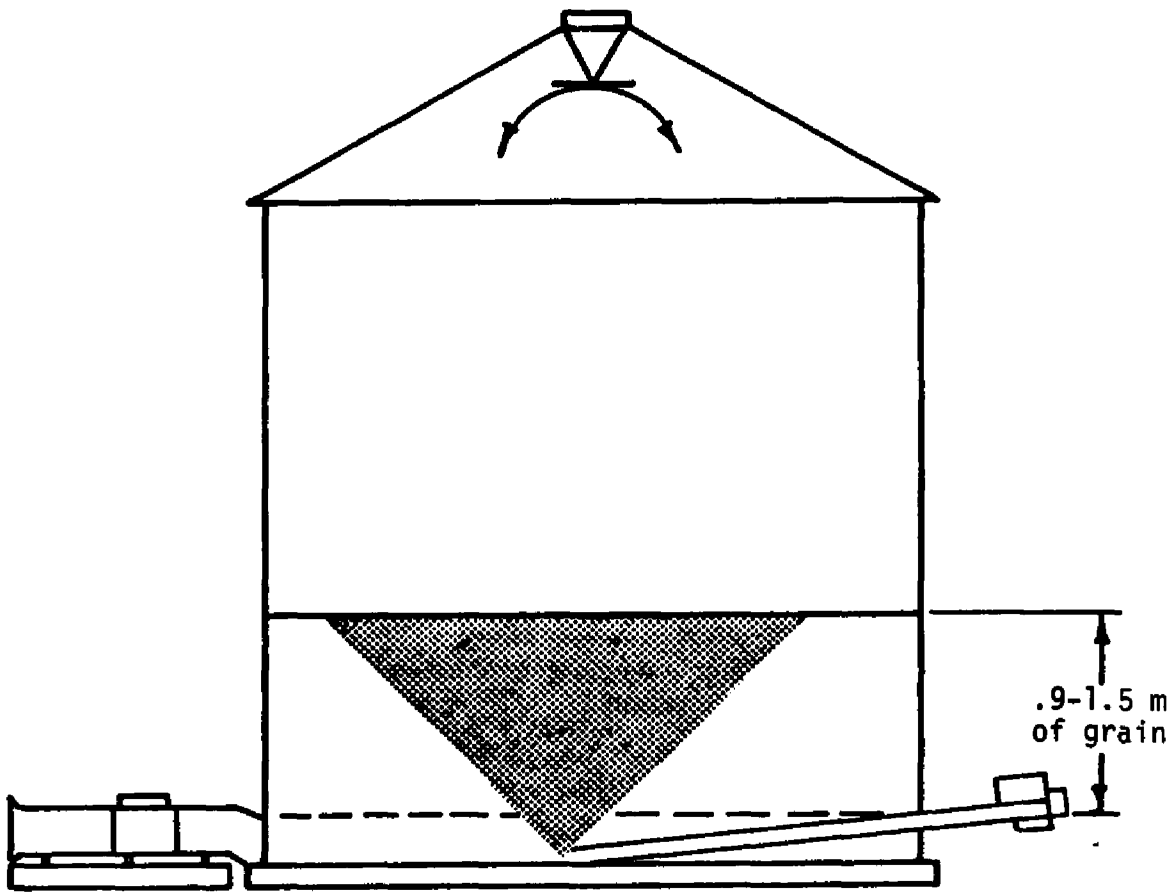


Figure 3. Parallel-flow or batch-in-bin system.

Note: A large gradient exists through the grain depth at completion of drying. The shaded area shows that a large amount of higher-moisture grain (top of mass) is drawn off with the first portion of grain removed (Brooker et al., 1978).

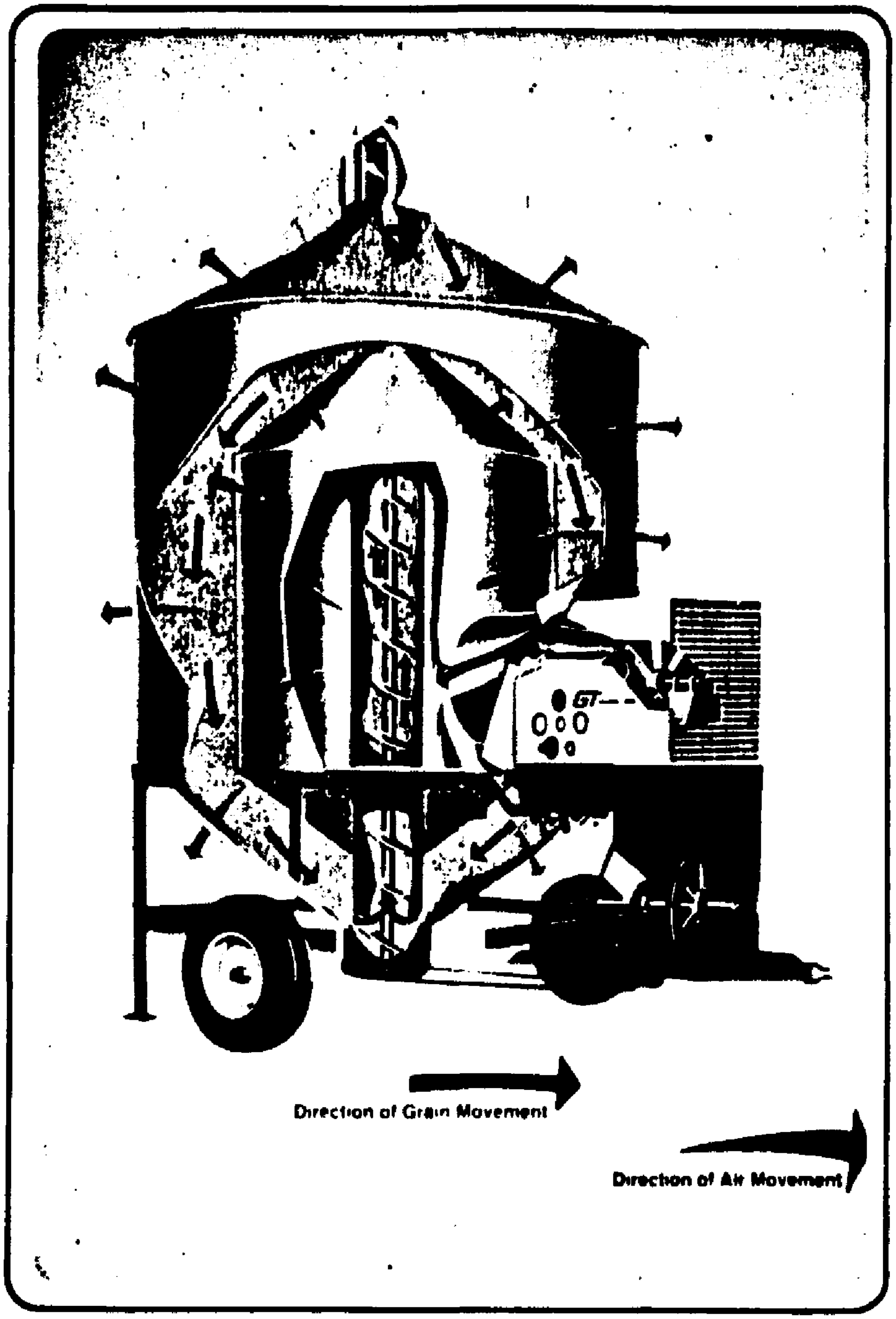


Figure 4. Internal view of a radial recirculating batch dryer. (From Gilmore and Tatge Mfg. Co., Inc., dealer manual.)

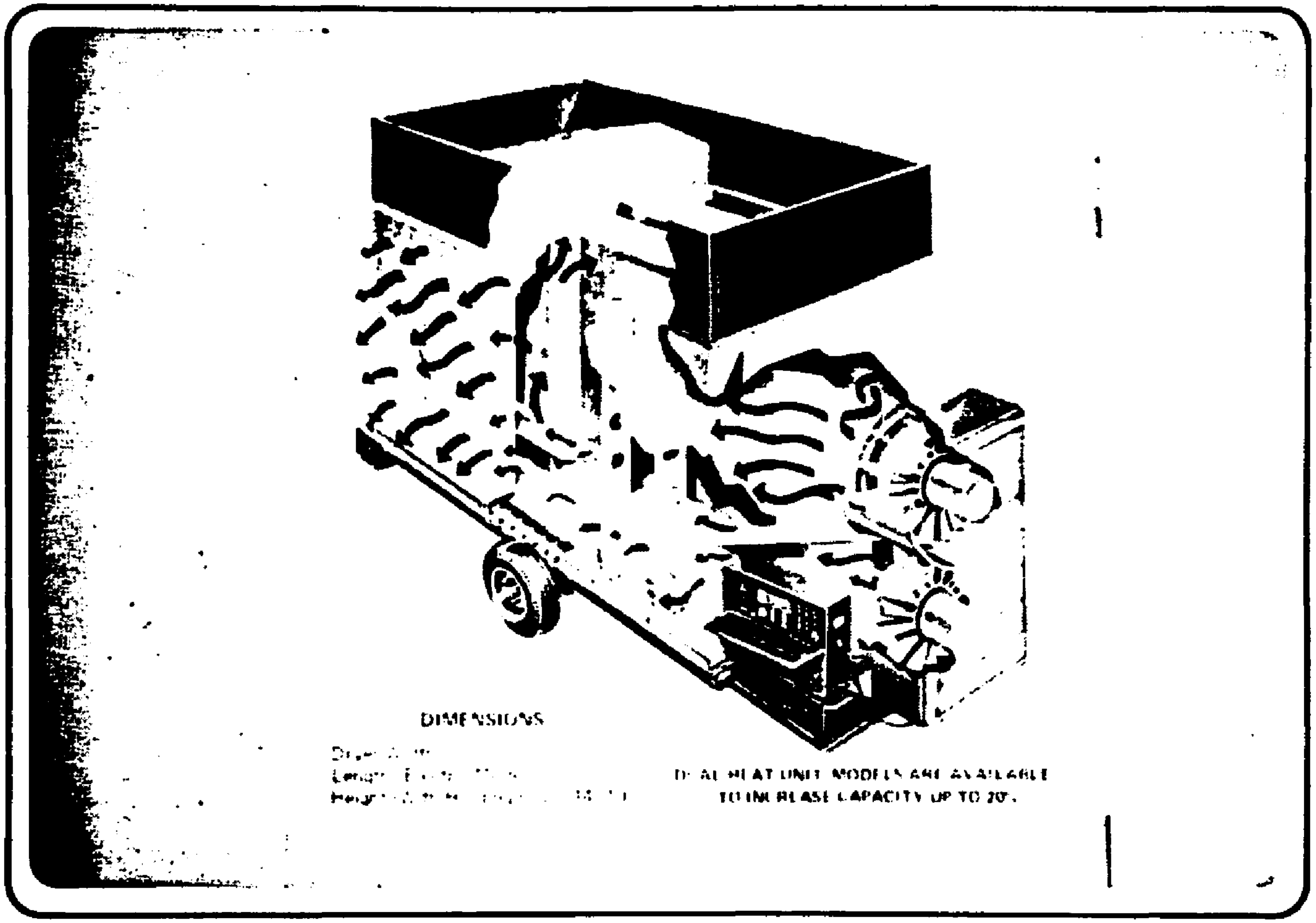


Figure 5. Internal view of a cross-flow batch dryer. (From Behlen Manufacturing Co., dealer manual.)

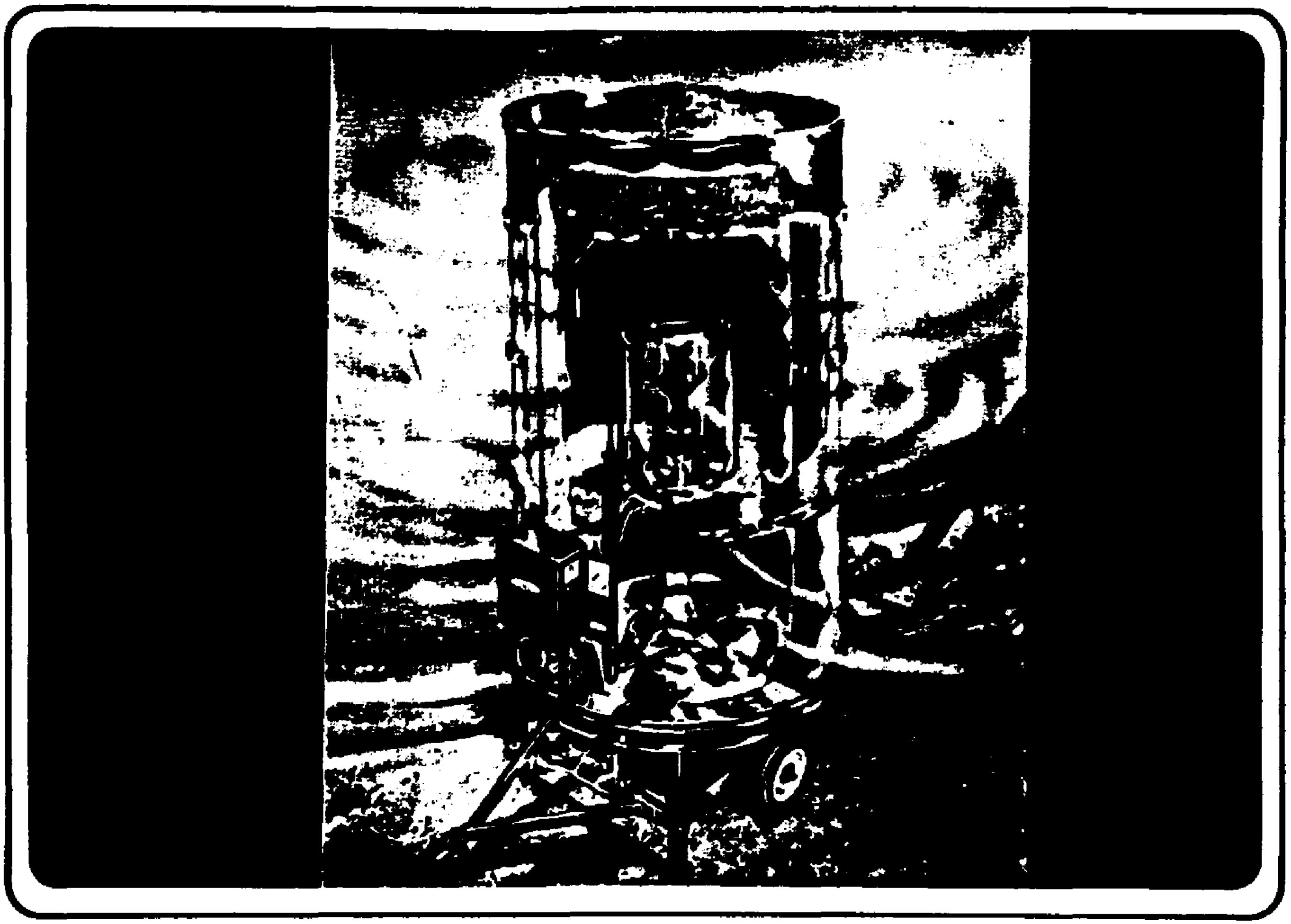


Figure 6. Internal view of a modified cross-flow dryer using warm exhaust air from the cooling section. (From Butler Manufacturing Co., workshop manual.)

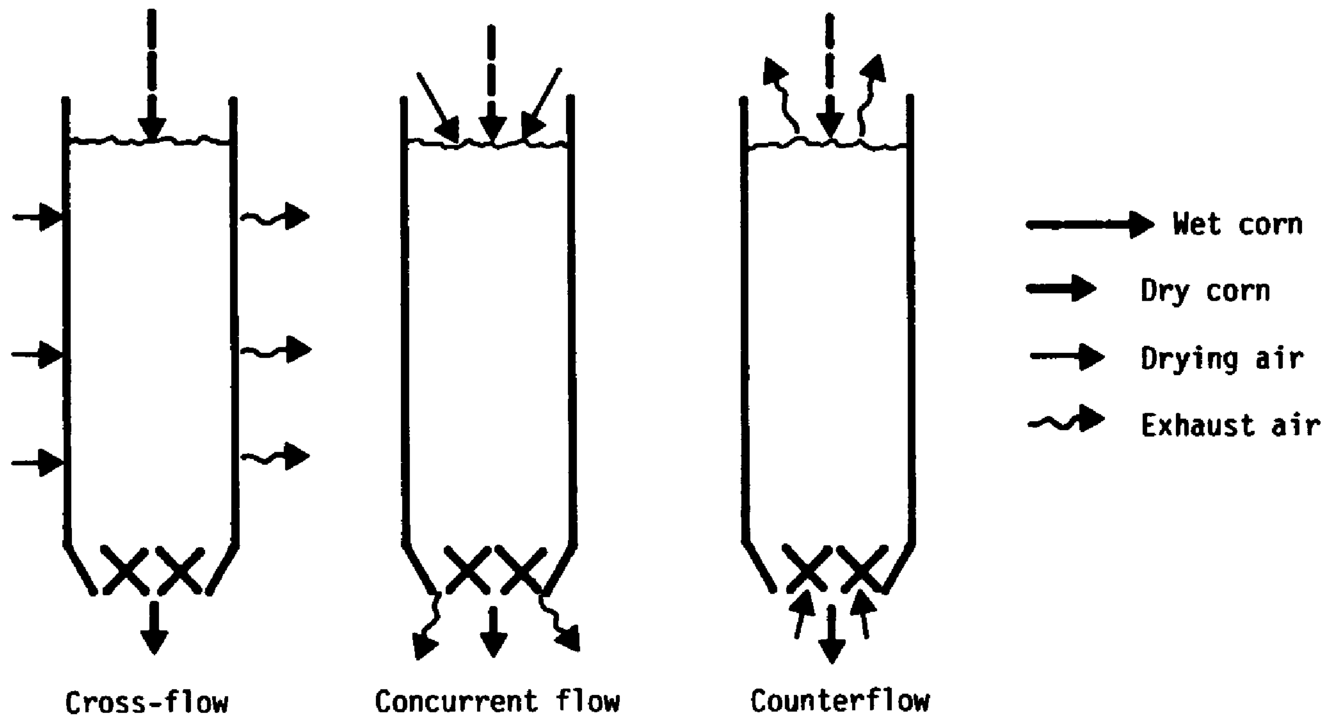
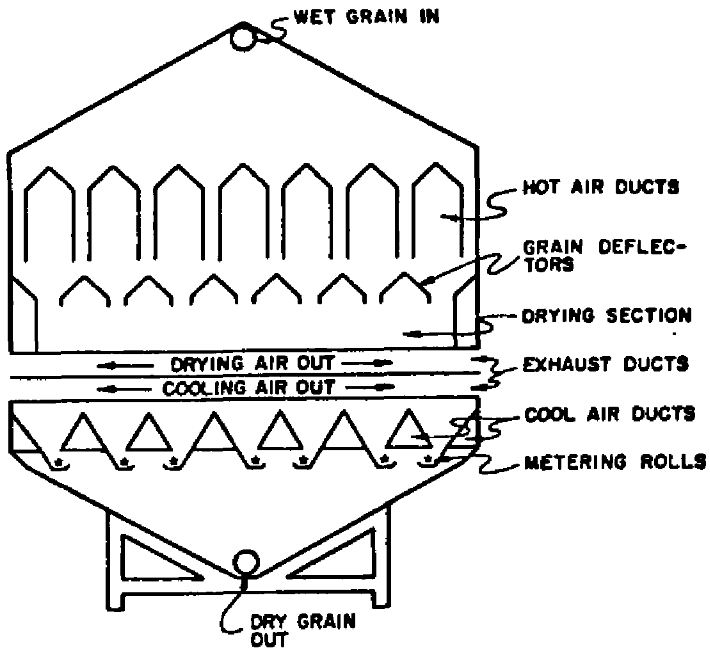
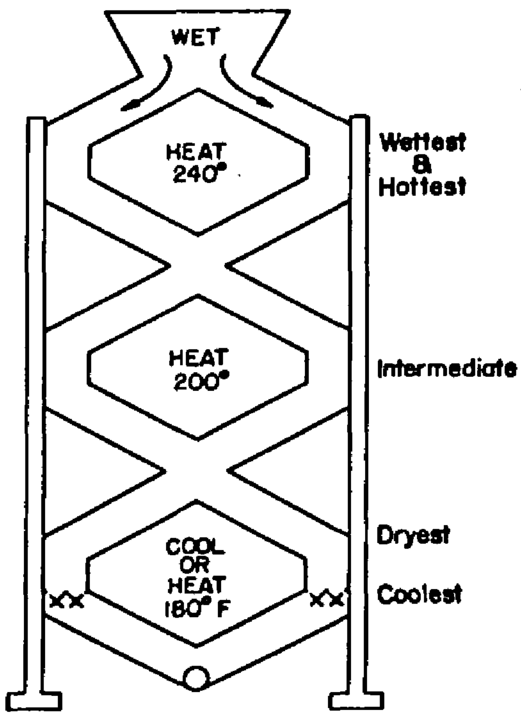


Figure 7. Illustration of the three types of continuous-flow dryers. (From Thompson et al., 1969.)



(a) Concurrent-flow dryer with counterflow cooling



(b) Multi-stage continuous-flow dryer

Figure 8. Schematic of high-speed continuous-flow dryers. (From Brooker et al., 1978.)

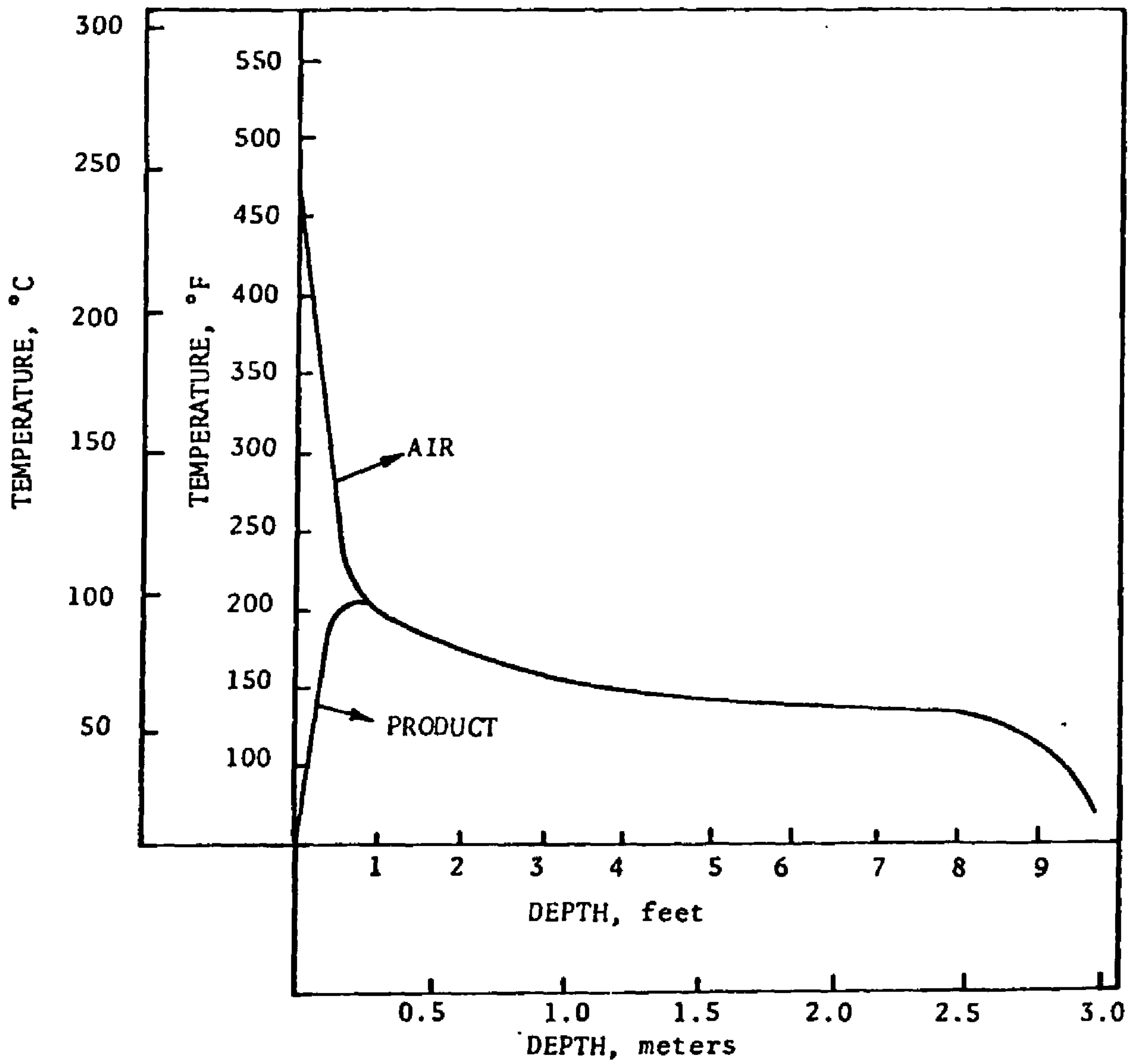


Figure 9. Air and product temperatures versus depth for a single-stage concurrent-flow dryer. (From Brooker et al., 1974.)

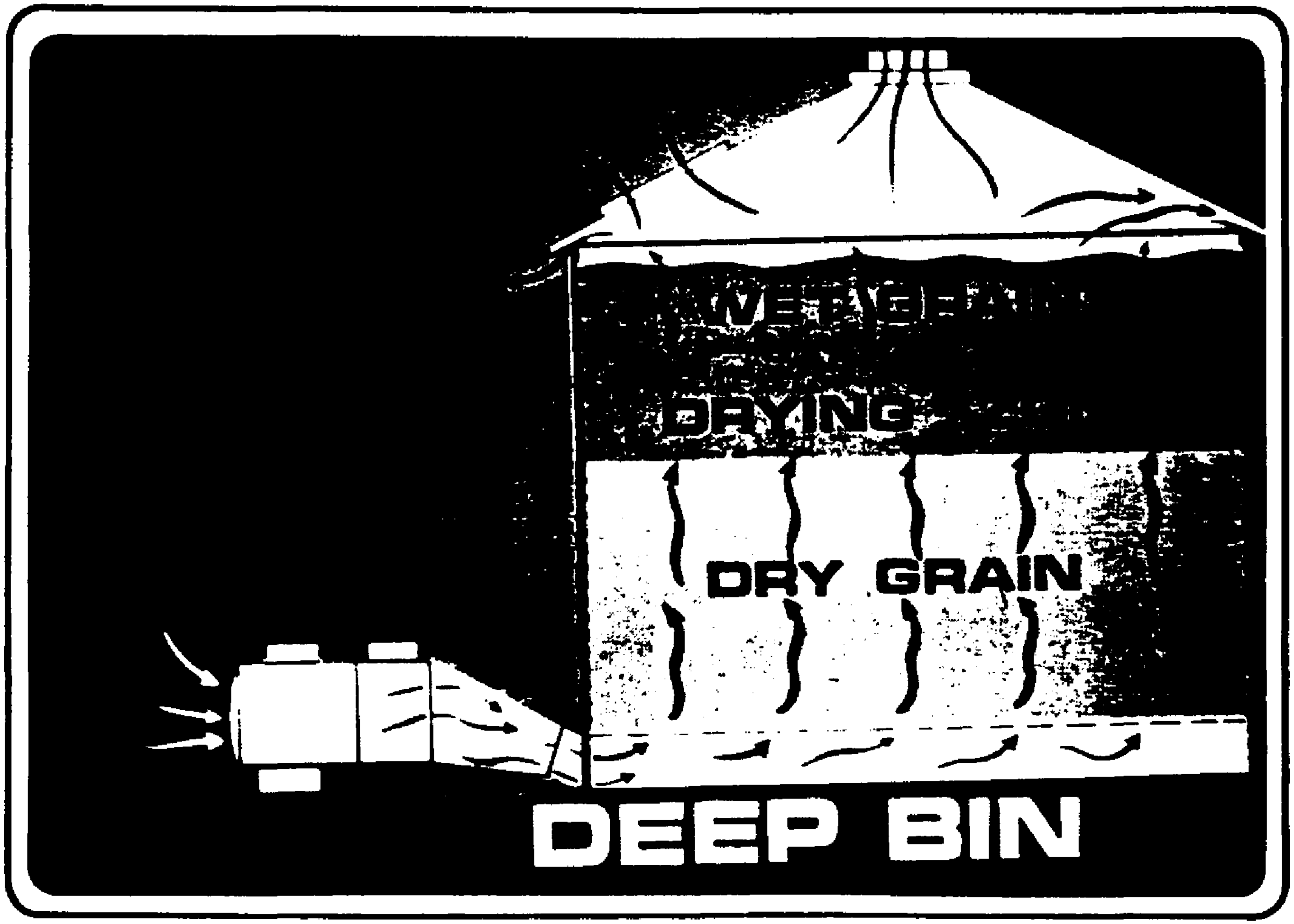


Figure 10. Schematic of a low-temperature in-bin drying system. (From Butler Manufacturing.Co., workshop manual.)

Table 3: Effect of harvest date and initial moisture content on the minimum airflow rate (cu m/min-t) required to dry corn with less than .5% dry matter loss. These airflow rates are for the next to worst year indicated by computer simulation tests using 10 years of actual weather data. A 1.1°C temperature rise from the fan motor was assumed.

Location	October 1				October 15				November 1			
	Initial Moisture Content				Initial Moisture Content				Initial Moisture Content			
	20%	22%	24%	26%	20%	22%	24%	26%	20%	22%	24%	26%
Bismarck, North Dakota	.32[a]	.61[a]	1.44	2.79	.35[a]	.48[a]	.63[a]	1.45	.40[a]	.55[a]	.67[a]	.98
Huron, South Dakota	.51[a]	1.45	2.68	4.57	.43[a]	.68[a]	1.56	3.55	.46[a]	.61[a]	.77[a]	1.17
Lincoln, Nebraska	1.04	1.99	3.39	4.73	.48[a]	1.29	2.30	4.32	.51[a]	.73[a]	1.20	2.48
Dodge City, Kansas	.57[a]	1.25	2.25	3.61	.39[a]	1.22	2.47	4.42	.37[a]	.61[a]	1.15	2.37
St. Cloud, Minnesota	.62[a]	1.55	3.38	4.76	.50[a]	.89	2.13	3.48	.47[a]	.63[a]	.81[a]	1.54
Des Moines, Iowa	.91	1.88	2.90	4.98	.64[a]	1.47	2.42	5.44	.70[a]	.92	1.20	2.62
Columbia, Missouri	.89	1.93	3.39	5.82	.60[a]	1.58	2.76	5.32	.48[a]	.91	1.97	3.09
Madison, Wisconsin	.67[a]	1.52	3.59	6.67	.53[a]	1.12	2.49	4.05	.46[a]	.68[a]	1.02	2.16
Chicago, Illinois	.80[a]	2.11	3.56	6.85	.61[a]	1.42	3.00	5.17	.49[a]	.76[a]	1.62	2.91
Indianapolis, Indiana	2.61	3.21	6.24	10.58	1.29	2.30	4.56	6.00	1.06	2.11	3.91	5.35
Indianapolis, Indiana[b]	1.01	2.92	5.07	8.24	.59[a]	1.23	2.08	3.50	.50[a]	.89	1.85	3.17
Lansing, Michigan	1.11	2.01	3.31	6.34	.83	1.99	3.06	4.33	.60[a]	1.07	1.95	3.40
Mansfield, Ohio	.91	2.07	3.60	5.50	.67[a]	1.37	2.84	6.75	.50[a]	.90	1.85	3.32
Midland, Texas	1.02	2.24	3.95	6.73	.71[a]	1.45	3.07	5.10	.38[a]	.91	1.89	3.12
Fresno, California	.86	1.61	3.05	4.88	1.38	2.32	4.00	5.86	1.20	3.01	5.29	6.52
Macon, Georgia	1.61	4.27	7.36	13.76	1.13	2.88	4.92	7.95	.81[a]	1.85	2.91	6.76
Cape Hatteras, No. Carolina	2.11	4.76	10.35	17.89	1.90	4.23	6.96	16.49	1.82	2.67	5.07	8.63
Sioux City, Nebraska	.64[a]	1.56	2.80	4.13	.63[a]	1.15	2.18	4.05	.54[a]	.72[a]	1.03	1.59
Grand Island, Nebraska	.39[a]	1.02	2.31	3.55	.36[a]	.82[a]	1.71	3.49	.38[a]	.54[a]	.92	1.45
North Platte, Nebraska	.32[a]	.75[a]	1.41	2.61	.30[a]	.44[a]	1.11	1.91	.34[a]	.51[a]	.63[a]	1.11
Scottsbluff, Nebraska	.23[a]	.48[a]	1.06	1.92	.24[a]	.39[a]	.71[a]	1.46	.27[a]	.40[a]	.63[a]	.97

Source: Pierce and Thompson (1978).

[a]Airflow rates below .83 cu m/min-t are considered aeration not drying. Rates larger than .93 cu m/min-t are recommended for drying.

[b]1.7°C continuous heat (in addition to the 1.1°C from the fan) was assumed for three simulation runs.

In a study of low-temperature grain drying in Wisconsin, Bartsch and Finner (1976) found that 27% moisture corn can be dried at low temperatures when unfavorable weather conditions exist if airflows of 2.6 to 3.7 $m^3/min/m^3$ of grain are provided. According to the authors, grain at a moisture content up to 30% can be successfully dried if 75% greater airflow is provided.

As an alternative source of heat for low-temperature drying systems, solar energy is considered to have potential. Direct application of solar energy has long been practiced in drying crops in the field, in the stack or windrow, on drying floors, and in ventilated sheds or cribs. Solar energy is not being used on a large scale to dry crops in the United States, even though much of the basic technology needed to develop solar systems is available (Buelow & Boyd, 1957; Lipper & Davis, 1960; Peterson, 1973; McLendon & Allison, 1978).

According to Peterson and Hellickson (1976), failure to employ solar energy for agricultural processes over the past decade, when much of the agricultural research was performed, was due to the availability of conventional energy sources at reasonable prices. The predominant factor in the adoption of solar energy for crop drying is that only a low temperature rise is needed, and this can easily be accomplished with low-cost flat-plate solar collectors. Efficiencies up to 70% for low-cost, low-temperature-rise solar collectors were reported by Sobel and Buelow (1963).

Two major problems encountered in natural-air and low-temperature drying are: (a) overdrying of the bottom layer, and

(b) the high airflow rate required for early harvested high-moisture corn (Pierce & Thompson, 1978; Bartsch & Finner, 1976). Two ways of preventing overdrying of the bottom layer are: (a) to remove the dry grain from the bottom of the bin, and (b) to avoid the drying-front formation by using stirring devices.

Roberts and Brooker (1975) determined the moisture profile from the top to the bottom of the grain mass within a recirculation dryer at several stages in the drying process. Figure 11 shows the curves generated by the mathematical model of the recirculation drying process.

Since 1965, stirring devices have been used to avoid overdrying in natural-air, low-temperature, and batch-in-bin drying (Williams et al., 1978).

It is difficult to design natural-air or low-temperature drying systems that guarantee successful drying without overdesigning them. It is critical to determine a minimum airflow. In their "simulation of stirred-bin low-temperature corn drying," Williams et al. (1978) concluded:

1. using a larger-than-recommended fan on an unstirred bin appreciably decreases drying time, with only a slight increase in operating and fixed costs;

2. using a stirring device allows a greater bed depth, with per-bushel cost equal to that of an unstirred bin with less depth;

3. the additional cost of a stirring device cannot be justified based on equal fill depth or equal weight of grain in an unstirred bin.

3.4.4 Combination Systems and Dryeration

A combination drying system is a system in which grain is partially dried in a high-temperature batch or continuous-flow dryer to a moisture content range of 18-22% wb and the final drying is completed in a low-temperature in-bin drying system (Shove, 1978; Brooker et al., 1978).

As a variant of combination drying, the widely practiced dryeration technique developed by Foster (1964) is a process involving the drying and aeration of the corn. The technique consists in removing the corn from the high-temperature dryer, without cooling, at a moisture content about 2-3% above the desired final value. Before the aeration phase, the corn is kept in a tempering tank for 6 to 10 hours and is finally cooled at low airflow (.4 to .8 $m^3/min/m^3$) (Brooker et al., 1978; Bakker-Arkema et al., 1978; McKenzie et al., 1972).

Studies conducted by Gustafson et al. (1976) and Shove and White (1977) indicated that the susceptibility to breakage was substantially reduced by eliminating rapid cooling of the high-temperature drying methods and rapid moisture-content decrease in the 18-15% range. According to Brooker et al. (1978), combination drying also offers the advantages of increased fuel efficiency and increased drying capacity.

3.4.5 In-Bin Counterflow Drying ("Shivvers System")

As previously stated, in-bin continuous-flow drying is classified as a counterflow process because the grain flows downward and the air flows in the opposite direction. The dried grain is removed from the bottom of the bin by means of a tapered sweep auger, which moves the grain to the center of the bin floor (Figure 12).

In this form of continuous or, more precisely, semi-continuous counterflow drying, the grain is hot when discharged from the dryer, and drying is completed by aeration in the storage bin or by the dryeration process. The hot drying air (approximately 71°C) enters the grain through the false floor and, as it moves upward, evaporation takes place.

The activation of the sweep auger is controlled by a temperature-sensing element placed about 46 cm above the false floor. As the drying progresses, the drying ratio in the region below the sensor decreases (less evaporation takes place), and the drying-air temperature at that point increases. When a preselected temperature is reached, the sweep auger is activated; it makes one complete cycle around the bin and removes an even, thin layer of dry corn. As the auger completes the cycle, damp grain moves into the sensor's region and the temperature at that point drops. The auger stops and waits for the next cycle.

According to Brooker et al. (1978), keeping a uniform depth of grain in the bin is of particular concern since an uneven grain depth causes uneven drying.

Counterflow dryers have the potential to remove more moisture per foot of dryer than any other type of continuous-flow dryers. Counterflow dryers make less efficient use of the internal energy of

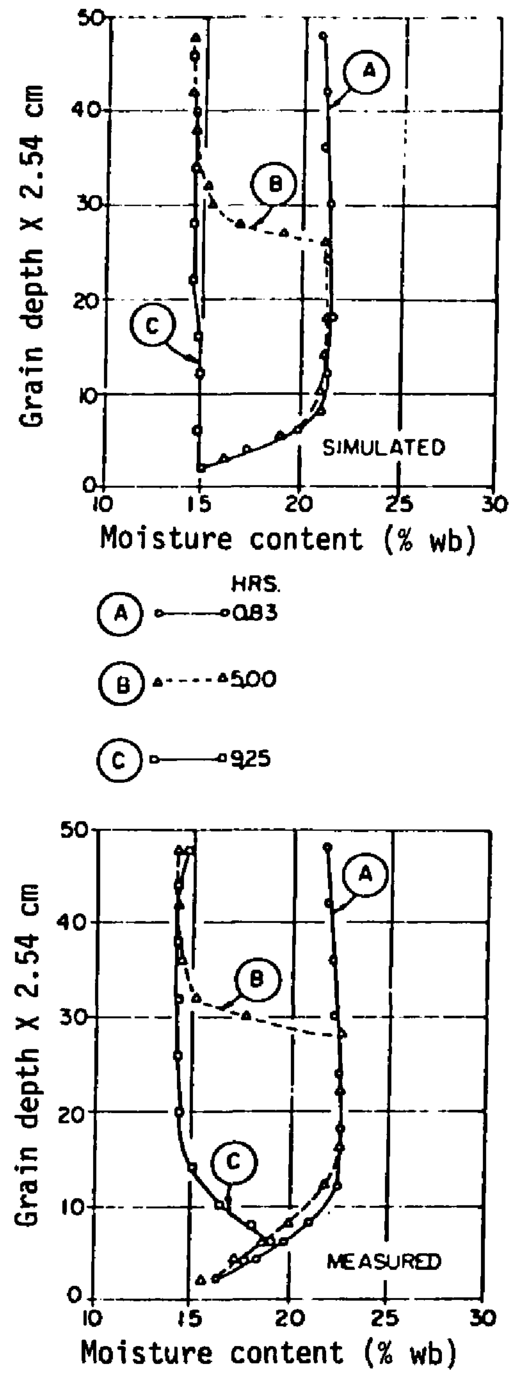


Figure 11. Grain moisture profile from the top to the bottom within a recirculation in-bin dryer with an airflow rate of 9.15 $m^3/min/m^2$. (From Roberts & Brooker, 1975.)

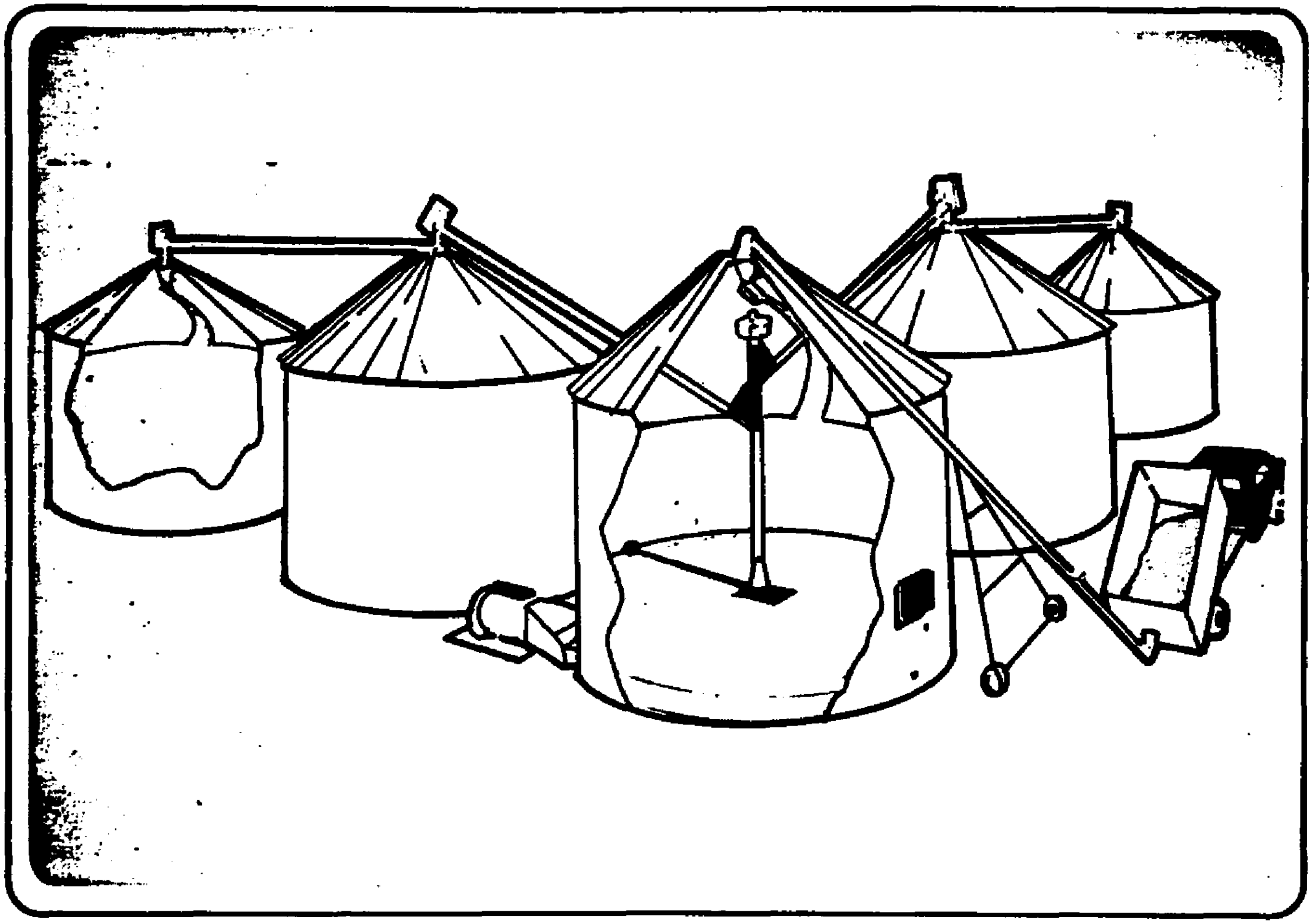


Figure 12. Schematic of the internal view of an in-bin counterflow drying "Shivvers System." (From Shivvers Corporation, dealer manual.)

the inlet air because more of the air's energy is used to heat the grain and, therefore, less energy is available for evaporation (Evans, 1970). However, assuming that the bed depth is sufficient to absorb virtually all of the drying potential of the heated air, the heat-use efficiency of the continuous-flow in-bin dryer is inherently high (Brooker et al., 1978).

In the in-bin counterflow system the bed depth can vary from .6 to 5 m although the high pressure drop at high depths will greatly reduce the air flow, resulting in a reduction of the dryer capacity.

Because of the high grain temperature (approximately 50°C) when the grain is discharged from the dryer, the moisture content can be 1-2% higher than desired. The final drying can be completed in a low-airflow cooling bin. If dryeration is used, 2-2.5% additional moisture can be removed. Technically, however, the added efficiency should not be attributed to the drying system since dryeration also works in other high-temperature drying systems delivering hot grain (Brooker et al., 1978).

3.5 Drying-System Evaluation

An evaluation of the factors affecting the economical operation and design of grain dryers requires that a cost analysis be performed. The costs may be classified as operating costs, fixed costs, timeliness costs, and miscellaneous costs.

Operating costs include costs of all heat and power sources and of labor. In most heated-air drying systems, the labor required to operate the dryer is assumed to be one-sixth of the operating time, or about three hours per day (Chang et al., 1979). In low-temperature drying systems, labor can be ignored because only periodic inspections are necessary.

Fixed costs constitute the major share of the total cost of a drying system. Interest rate, depreciation, taxes, and insurance are referred to as fixed costs (Young & Dickens, 1975; Bridges et al., 1979; Skees et al., 1979).

Most authors do not consider timeliness costs and costs represented by reduced value of grain quality because there is no way to measure these costs accurately.

According to Hukill (1947) and Young and Dickens (1975), all of the aforementioned costs are affected in one way or another by the length of time required to dry the product. Therefore, to predict the costs for drying, it is necessary to predict the required drying time.

The manner in which water is removed from grain or other biological products has been the subject of much research. Brooker et al. (1974) indicated that six modes of moisture removal are possible: (a) liquid movement due to surface forces (capillary flow), (b) liquid diffusion due to moisture-concentration difference (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), and (f) water and vapor movement due to total-pressure differences (hydrodynamics flow). The manner in which water is removed from the grain is indirectly affected by air temperature, air velocity, moisture concentration, and product type and condition (Stevens et al., 1978).

In recent years, a number of mathematical models have been proposed to describe the bulk drying of agricultural products. Hamdy and Barre (1970) classified the drying models into two categories:

1. Rational models, in which a set of equations derived from theory is applied. The equation system is normally large, and a number of simplifying assumptions must be made to permit solution.

2. Empirical models, in which an attempt is made to analyze experimental data and to formulate an expression, normally based on a statistical solution, to describe the drying process. According to Brooker et al. (1974), the resulting equations can predict the drying process only within the temperature and moisture-content range and for the particular grain for which the equations have been developed.

Among the rational models developed to predict the bulk drying of grain are those by Boyce (1965), Bakker-Arkema et al. (1967), Henderson and Henderson (1968), Thompson et al. (1968), and Hamdy and Barre (1970). Although these models are said to provide a better description of the drying process than the empirical models, some require extensive and sophisticated computer-programming techniques and sometimes considerable computer time for solution.

3.5.1 Drying Equations

Hukill (1954) analyzed deep-bed drying and derived the following equation, which is less accurate than the previously mentioned models but useful for design purposes:

$$\frac{\partial M}{\partial t} = P \frac{\partial T}{\partial x} \tag{1}$$

where $P = \frac{6000\ \dot{m}\ cp}{W\ h}$, a constant for any given set of drying conditions

$\dot{m}$ = mass flow rate (Kg/m^2 min)

h = latent heat of vaporization of moisture in the grain (KJ/Kg)

W = density of dry matter (Kg/m^3)

cp = specific heat of dry air (KJ/Kg °C)

For grain fully exposed to constant drying conditions (such as grain at the very bottom of a bin), and for air moving through grain of uniform moisture content (such as a batch of grain at the beginning of the drying process), the following approximations can be made (Hukill, 1954):

for the moisture: $$M - Me = (Mo - Me)\ e^{-kt} \tag{2}$$

and

for the grain temperature: $$T - Tg = (To - Tg)\ e^{-cx} \tag{3}$$

in which $$c = \frac{k(Mo - Me)}{P(T - Tg)}\ .$$

Hukill proposed the following solution:

$$M = (Mo - Me)\ \frac{e^{cx}}{e^{cx} + e^{kt} - 1} + Me \tag{4}$$

and

$$T = (To - Tg)\,\frac{e^{kt}}{e^{cx} + e^{kt} - 1} + Tg \tag{5}$$

Expressing moisture content in terms of the moisture ratio,

$$\overline{MR} = \frac{M - Me}{Mo - Me}\,, \tag{6}$$

the drying time can be expressed in terms of the period of half response (one period [H] is the time required for a fully exposed grain layer to reach a moisture ratio equal to 0.5 under a given set of conditions). Then, $e^{-kH} = 0.5$ or $e^{kH} = 2$; and the time, in periods of half response, is

$$Y = t/H\,. \tag{7}$$

The unit of equivalent depth (D'), as defined by Hukill (1954), is the depth that contains enough grain to attain the heat requirement for evaporating its moisture, from an initial moisture ratio of MR = 1.0 to a final moisture ratio of MR = 0. The heat requirement must be equal to the sensible heat supplied by all air in one unit of time if its temperature is dropped from To to Tg. At any level in the bin, the equivalent depth is:

$$D = \frac{x\ A\ W\ h\ (Mo - Me)}{Cp\ m\ H\ (To - Tg)} \tag{8}$$

If these units are used,

$$MR = \frac{2^{D}}{2^{D} + 2^{Y} - 1} \tag{9}$$

Figure 13 is the graphical representation of Equation 9.

The relationships proposed by Hukill have been used to describe drying in batch and crossflow drying systems (Young & Dickens, 1975). Barre et al. (1971) expressed Equation 9 in terms of base e rather than base 2 and developed the following expressions:

$$\overline{MR} = \frac{1}{D'} \ln \left(\frac{e^{D'} + e^{Y'} - 1}{e^{Y'}}\right) \tag{10}$$

and

$$t_H = \ln \left(\frac{e^{D'} - 1}{e^{\overline{MR}\, D'} - 1}\right) \tag{11}$$

Equation 10 represents the mean moisture ratio ($\overline{MR}$) and Equation 11 represents the drying time (t_H) required to obtain a desired moisture ratio. Based on the same procedure, Young and Dickens (1975) developed similar equations in terms of base 2:

$$\overline{MR} = \frac{\overline{M} - Me}{Mo - Me} = \frac{1}{(\ln 2)D} \ln\left(\frac{2^D + 2^Y - 1}{2^Y}\right) \tag{12}$$

and

$$t_H = YH = \frac{H}{\ln 2} \ln\left(\frac{2^D - 1}{2^{\overline{MR}\, D} - 1}\right) \tag{13}$$

Hukill's (1954) and Barre et al.'s (1971) dimensionless depth and time variables have the following relationship:

$$Y' = Y \ln 2 \tag{14}$$

and

$$D' = D \ln 2 \tag{15}$$

Equation 13 is simpler and can be solved for drying time more quickly than the more sophisticated models. The time determined by

Young and Dickens' (1975) equation (Equation 13) is an estimation of the time required to dry a batch of grain or the time the grain must remain in the drying section of a continuous cross-flow dryer. The time a thin layer of grain must remain at the bottom of the bin in an in-bin counterflow system to reach a given final average moisture content can likewise be estimated.

To calculate the moisture ratio at any time during the drying process, the equilibrium moisture content of the product must be calculated for the inlet air conditions. A number of theoretical, semi-theoretical, and empirical models have been proposed for calculating the moisture equilibrium of a cereal grain. Because of its simplicity, the Silva relationships for equilibrium moisture were chosen (Kalchik et al., 1979):

For $0 > RH \leq 52.0$,

$$Me = \frac{7.4776\ RH^{.4584}}{\ln(\frac{9T}{5} + 32)} \tag{16}$$

and for $52.0 > RH \leq 99.9$,

$$Me = \frac{21.2198\ \exp(.0146\ RH)}{\ln(\frac{9T}{5} + 32)} \tag{17}$$

To solve Equation 13, the time of half response (H) must be known. It is determined from the exponential drying equation, which is assumed for thin-layer drying (Equation 18):

$$\frac{M - Me}{Mo - Me} = e^{-kH} = \frac{1}{2} \tag{18}$$

where the thin-layer drying constant (k) is given by Equation 19 (Brooker et al., 1974):

$$k = 5.4 \times 10^{-1} \exp(-5023/\tfrac{9}{5}\,\mathrm{Tabs}) \tag{19}$$

3.5.2 Basic Assumptions

Besides the assumptions made by Hukill (1954), the following additional assumptions must be made in order to apply the Hukill procedure to predict the drying time of an in-bin counterflow dryer ("Shivvers System"):

1. the dryer is a batch dryer with a deep bed (larger than 1 m).

2. the characteristics of the air entering the grain bed are constant;

3. the initial grain moisture content is constant;

4. the bed depth is constant and leveled by means of a grain spreader located at the entrance to the dryer;

5. the grain bed is divided into layers of equal depth (x); the difference in dry-matter content between the layer being dried and the next layer is negligible;

6. the average moisture content for each layer, after the lowest layer has been dried, is the log-mean between the lower and upper edges of the adjacent layers;

7. the tapered sweep auger removes the dried layer of grain at the bottom of the bin at the desired final moisture content with no effect on the uniformity of the drying front;

8. the drying progresses as shown schematically in Figure 14.

Under the above assumptions, it will be guaranteed that:

1. the exhaust drying air is always saturated as it leaves the upper surface at a temperature equal to the inlet drying air wet-bulb temperature (assumptions 2, 3, and 4);

2. the drying rate is constant (assumptions 2, 3, and 4);

3. the static pressure is constant and, as a consequence, a uniform drying front exists (assumption 4);

4. calculation of the distance of the kernels from the bin floor with the average moisture content in the second layer is facilitated (assumption 6);

5. the drying time or time between two consecutive cycles can be calculated at the beginning or at the end of each cycle (assumption 7).

Excluding the assumptions (1, 5, 6, 7, and 8) inherent in the in-bin counterflow system, all the other assumptions must be made in order to predict the time required to achieve the desired final average moisture content in a cross-flow batch dryer.

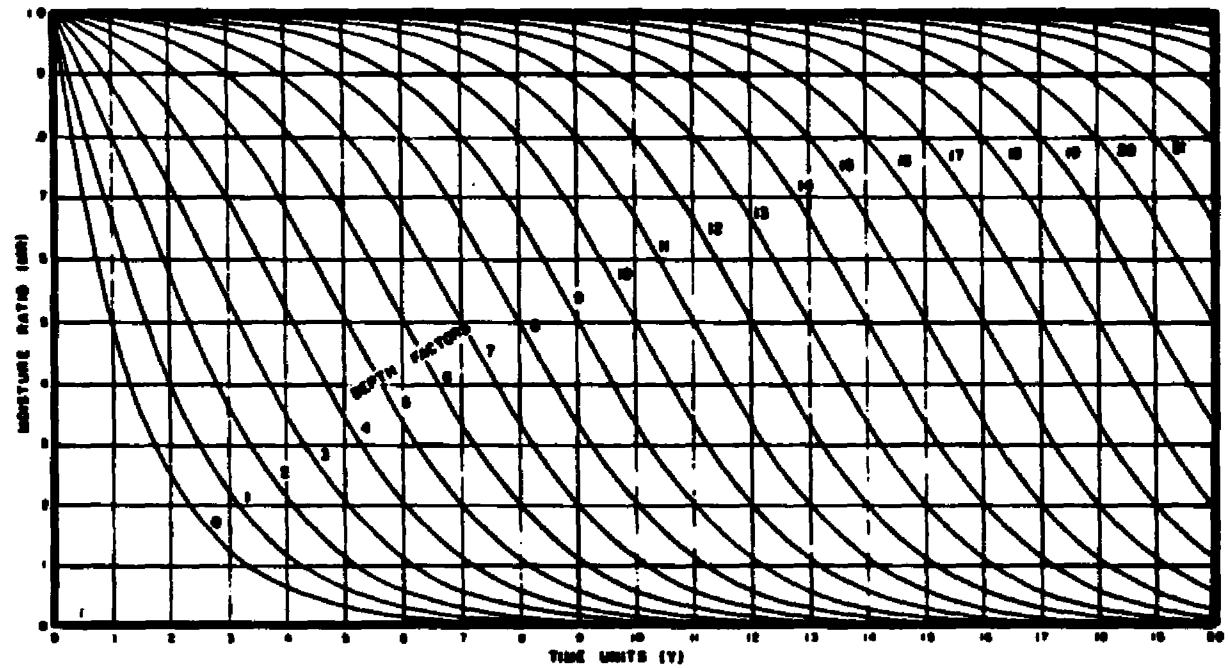


Figure 13. Deep-bed drying curves. (From Hukill, 1954.)

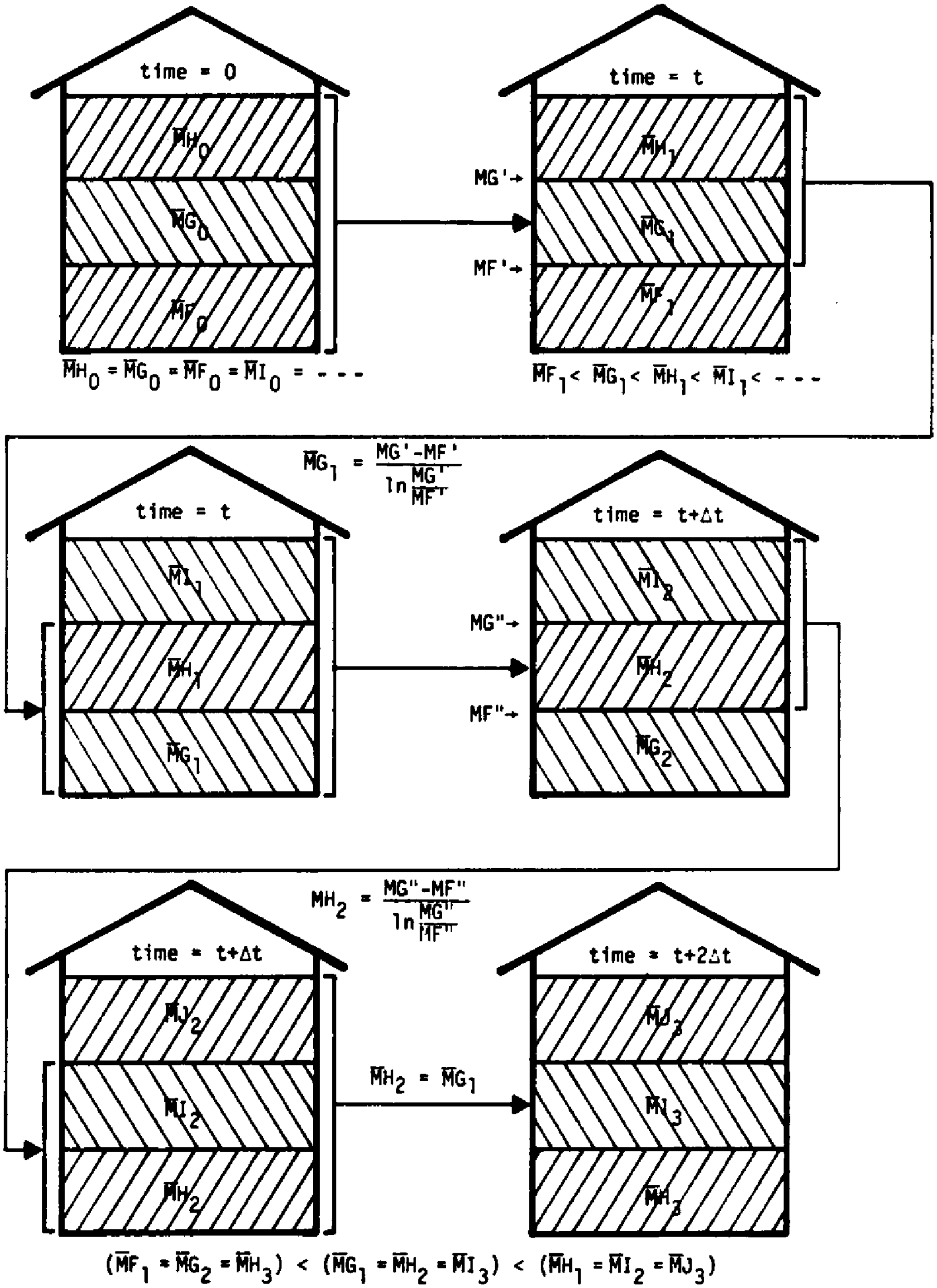


Figure 14. Schematic of the in-bin counterflow drying system.

4. EXPERIMENTAL

Described in the following section are the conditions under which the tests were performed at the Kalchik Farms in Bellaire, Michigan, and how the on-farm drying and storage system was designed. Although products other than corn can be dried and stored in the actual systems, they were designed based on corn.

4.1 Test Location

Five alternative corn-drying techniques were tested on a commercial farm in Bellaire, Michigan, during the 1978 and 1979 fall harvest seasons. The region where the farm is located is not considered a prime corn-growing area. However, high harvest moisture content and unfavorable climatic conditions were the reasons for choosing the experiment location. It can thus be argued that any drying technique that operates successfully in Bellaire, Michigan, will work at any farm in the lower peninsula of Michigan.

The five alternative drying systems include:

1. high temperature/natural air combination drying
2. high temperature/low temperature (electric heat) combination drying
3. in-bin dryeration
4. in-bin counterflow drying
5. conventional batch drying.

4.2 Design of Alternative Drying System

Five steel bins of 84.6 m^3 capacity were arranged in a pattern to allow multiple use and flexibility. The system was designed to effectively test each drying technique and to handle the farm's corn production. Four storage bins were set up in a rectangular pattern so that each could be filled with an auger from the central point (Figure 15). Two of the storage bins were set up as combination drying systems. The first had a centrifugal fan with a 3.7 Kw motor delivering 2.0 m^3 of natural air per min/m^3 of grain through a 3.7 m bed. A fan delivering 1.6 m^3 of air per min/m^3 of grain with a 2.2 Kw motor and a 20 Kw electrical resistance heater were part of the low-temperature bin drying system. The third bin was fitted with a fan delivering 0.8 m^3 of air per min/m^3 of grain for in-bin dryeration. To the fourth bin a grain airflow rate of 0.3 m^3 of air per min/m^3 of grain was applied to cool hot grain from the in-bin counterflow dryer mounted in the adjacent fifth storage bin.

Wet corn from the field entered the installation through either the in-bin counterflow system or the wet holding tank for the cross-flow system. Figure 16 is a general view of the installation.

All of the storage bins have full perforated floors with steel support legs to insure uniform airflow through the entire bin. The roofs were installed with a 12.7 mm gap over the side walls so that condensation under the roof would drip outside the bin wall. Roof vents were installed to reduce the exhaust-air velocity to less than 0.3 m/sec.

Ports were drilled into the plenum under each bin to check the static pressure of the fans for determination of airflows. Thermocouples (copper-constantan) were suspended from the roofs at 0.3 m intervals on a cable with one cable per bin. All thermocouples were connected through an underground network to an instrument shelter for central recording.

The conventional cross-flow batch dryer (Figure 17 and Table 4) dried batches of approximately 4.2 m^3 of wet corn; the initial drying-air temperature was 104°-115°C, and the final temperature was 82°C. The in-bin counterflow system (Figures 18 and 19 and Table 5) dried at 71°C. Both high-temperature systems used liquid propane as fuel.

4.3 Drying Procedures

Corn (DeKalb XL-12) was harvested during the 1978-1979 season under favorable weather (sunny, no rain), November 1-24. The initial moisture content varied from 30% wb at the start to 23% wb at the end of the harvesting season. The daytime temperature varied between 7° and 18°C, and the nighttime temperature between 2° and 6°C. A total of about 531 m^3 of corn was dried.

The tests were repeated during the 1979-1980 season under unfavorable conditions (with considerable rain and long periods of high relative humidity), November 3-25. The initial moisture content varied from 31-38% wb. The daytime temperature varied between 7.2° and 14.5°C, and the nighttime temperature between -1° and 4.5°C.

Table 4: Dryer specifications of Farm Fans dryer model AB-8B, 1978 model.

Grain column length, ft		1
Total holding capacity, bu		120
Less transport:	Length, ft	13.25
	Width, ft	6.00
	Height, ft	8.75
With transport:	Length, ft	16.16
	Width, ft	7.75
	Height, ft	10.00
Fan horsepower		10-13
Fan diameter, in.		28
Airflow at 3 in. static pressure		15,000 cfm
Heater capacity, BTU/hr		3,000,000
Top auger, HP		1
Top auger capacity, Bu/Hr		1,500
Bottom auger, HP		1
Bottom auger capacity, Bu/hr		900
Max. running amps., 1 ph., 230 V (with 5 HP load and unload conveyor)		90
Max. running amps, 3 ph., 220 V. (with 6 HP load and unload conveyor)		60
Drying capacity, wet Bu shelled corn per hr		
Dry and cool, 25% to 15%		110
Dry and cool, 20% to 15%		155
Full heat, 25% to 15%		150
Full heat, 20% to 15%		210

*Excluding load and unload time

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

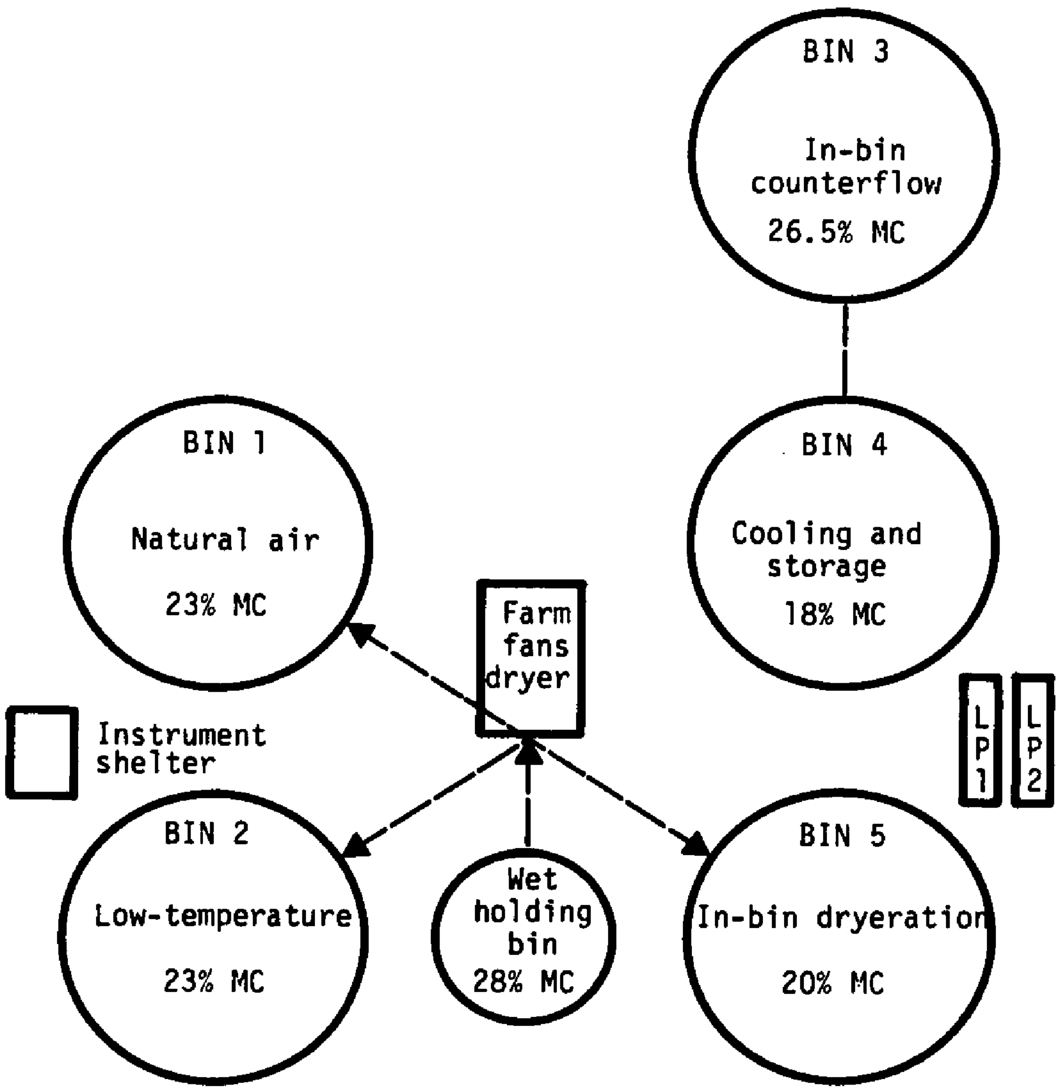


Figure 15. Schematic of the location of the various drying modes at the Kalchik Farms at Bellaire, Michigan.

Figure 16. General view of the Kalchik installation.

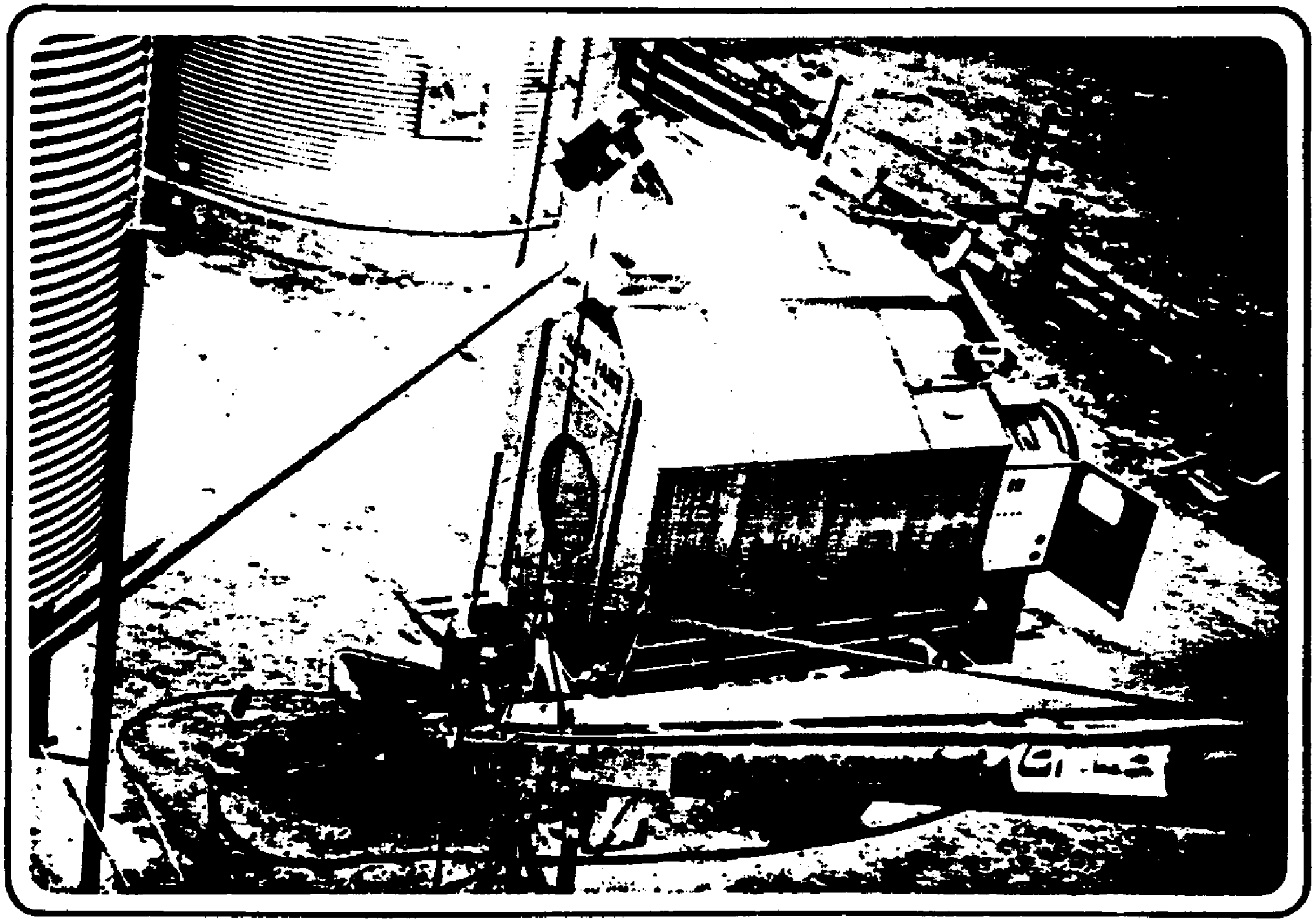


Figure 17. Farm Fans automatic batch model AB-8B (3-ton capacity).

Figure 18. View of the total in-bin counterflow "Shivvers System."

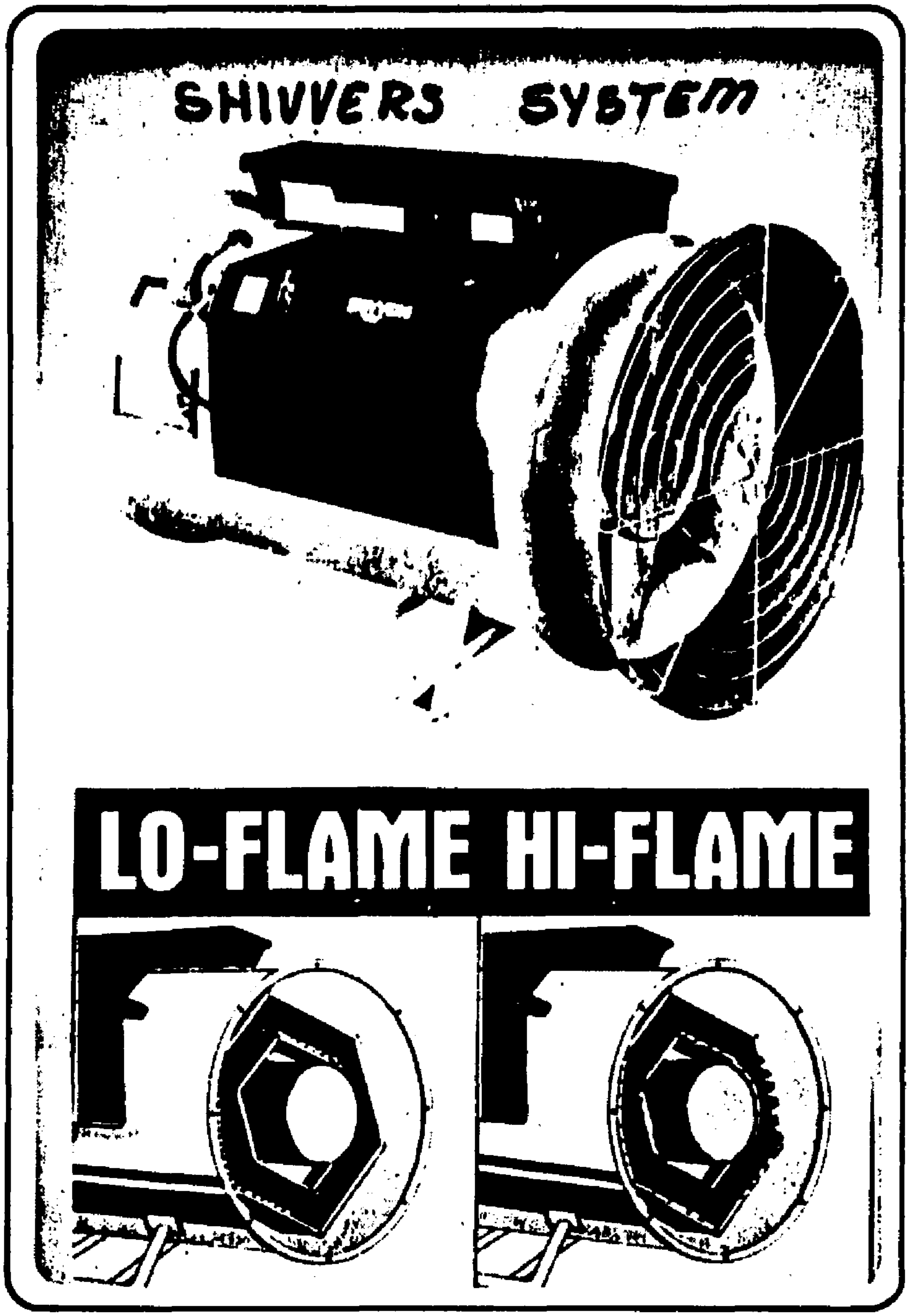


Figure 19. Details of the 13 HP blue flame "Shivvers System." (From Shivvers Corporation, dealer manual.)

Table 5. In-bin counterflow dryer specifications for "Shivvers Systems."

	Number of Fans	Horsepower	Description	Static Pressure	Air Delivery	Bushels/ Hour	Bushels/ Day
18 ft.[a] diam. bin	1	5 HP	22" Vane Axial	2.90"	8,600 CFM	61	1464
	1	7.5 HP	22" Vane Axial	3.40"	9,500 CFM	68	1632
	1	10 HP	Centrifugal	4.50"	11,500 CFM	82	1968
	1	13 HP	BLUE FLAME	4.50"	11,500 CFM	82	1968
21 ft. diam bin	1	7.5 HP	22" Vane Axial	2.45"	10,500 CFM	75	1800
	1	10 HP	26" Vane Axial	3.05"	12,250 CFM	87	2088
	1	10 HP	Centrifugal	3.20"	12,500 CFM	89	2136
	1	13 HP	BLUE FLAME	3.70"	13,750 CFM	98	2352
24 ft. diam. bin	1	7.5 HP	22" Vane Axial	1.75"	11,250 CFM	80	1920
	1	10 HP	26" Vane Axial	2.00"	12,600 CFM	90	2160
	1	10 HP	Centrifugal	2.20"	13,250 CFM	94	2256
	1	20 HP	Centrifugal	3.40"	17,000 CFM	121	2904
	2	7.5 HP	22" Vane Axial	3.65"	17,750 CFM	127	3048
	1	20 HP	30" Vane Axial	3.95"	18,500 CFM	132	3168
	1	13 HP	BLUE FLAME	3.00"	15,750 CFM	112	2688
	2	13 HP	BLUE FLAME	4.82"	20,900 CFM	148	3552
27 ft. diam. bin	1	10 HP	26" Vane Axial	1.72"	14,500 CFM	103	2472
	2	7.5 HP	22" Vane Axial	3.05"	20,000 CFM	143	3432
	1	20 HP	30" Vane Axial	3.15"	20,400 CFM	145	3480
	2	10 HP	26" Vane Axial	3.58"	22,200 CFM	158	3792
	2	10 HP	Centrifugal	4.00"	23,750 CFM	169	4056
	1	13 HP	BLUE FLAME	2.30"	16,750 CFM	119	2856
	2	13 HP	BLUE FLAME	4.20"	24,700 CFM	175	4200
30 ft. diam. bin	1	10 HP	26" Vane Axial	1.40"	15,000 CFM	107	2568
	1	10 HP	Centrifugal	1.27"	13,800 CFM	98	2352
	1	20 HP	Centrifugal	1.88"	18,000 CFM	128	3072
	2	7.5 HP	22" Vane Axial	2.40"	21,300 CFM	152	3648
	1	20 HP	30" Vane Axial	2.50"	21,650 CFM	154	3696
	2	10 HP	26" Vane Axial	3.00"	24,500 CFM	174	4176
	1	13 HP	BLUE FLAME	1.80"	17,500 CFM	124	2976
	2	13 HP	BLUE FLAME	3.65"	27,750 CFM	197	4728
36 ft. diam. bin	1	20 HP	30" Vane Axial	1.58"	23,500 CFM	167	4008
	2	10 HP	26" Vane Axial	2.08"	28,000 CFM	199	4776
	2	20 HP	30" Vane Axial	3.53"	39,000 CFM	277	6648
	2	20 HP	Centrifugal	2.94"	34,750 CFM	247	5928
	1	13 HP	BLUE FLAME	1.10"	18,300 CFM	130	3120
	2	13 HP	BLUE FLAME	2.60"	32,000 CFM	227	5448

These are realistic estimates. Drying conditions are 50° outside air at 70% rh., drying air 160°, initial corn temperature 50°, grain depth 6 ft., 25% corn dried to 15%.

Model 1328 Single and Three-Phase Specifications[a]

Fan Diameter. . . . . .28-1/4 inch
Blade . . . . .6 blade axial
Motor . . . . .13 HP, open drip proof
Motor Protection . . .Manual reset overload relay
Magnetic Starter . . .Rugged 60 Amp. magnetic starter standard on single and three-phase models
Burner Construction . .Heavy wall 16-gauge stainless steel ring burner
Burner Capacity . . . .3,650,000 BTU per hour maximum capacity. Produces 160°F heat rise

Vaporizer . . . Fully adjustable vaporizer with high temperature protection standard on LP models
Gas Strainer . Vapor strainer on propane and natural gas burners. Liquid strainer standard on liquid propane models.
Regulator . . . Pressure regulator and pressure gauge standard on all models.
Ignition . . . Continuous 10,000 volt transformer ignition with heavy duty ignition plug

Source: Shivvers Corporation, dealer manual.

[a]Dryer model used at Kalchik Farms.

The corn was cleaned in a rotary cleaner before dumping it in a 44 m^3 wet holding bin or into the in-bin counterflow dryer. From the wet holding tank, the corn was transported in a 15.3-cm auger to the automatic batch dryer and dried to the required moisture content. The grain was conveyed from the dryers into one of the 84 m^3 drying-storage bins. The intermediate moisture content of the corn after partial high-temperature drying in the batch dryer and before dumping it hot into the natural-air combination drying bin and the low-temperature combination drying bin was about 23%; in the case of the in-bin dryeration bin, it was about 20%.

The conventional batch-drying technique (control treatment) consisted of drying wet corn directly to 15.5% wb. For the in-bin counterflow system, the corn was dried to about 18.5% wb and was then finally dried to 15.5% wb in the auxiliary aeration bin.

4.4 Instrumentation and Measurement

The parameters required for rating the drying capacity and energy efficiency of a dryer are: (a) grain inlet moisture content, (b) drying-air temperature, (c) grain inlet temperature, (d) ambient-air relative humidity, (e) fuel (liquid propane and electricity) consumption, (f) airflow rate, (g) corn test weight, (h) BCFM, (i) ambient temperature, (j) drying and cooling time, (k) loading time, (l) unloading time, and (m) number of bushels per batch or per cycle in the in-bin counterflow system.

The number of bushels per batch or per cycle was determined by directly weighing the dried grain as it was delivered to a commercial buyer. Thus, dryer capacity was determined by dividing the total weight of the dried corn by the number of batches or cycles.

The approximate grain moisture content of the corn samples was determined during on-farm drying operations with a capacitance-type moisture meter. Samples were collected before and after drying. Each sample was later checked with the standard oven method (72 hours at 103°C).

The inlet and exhaust drying-air temperatures were measured by copper-constantan thermocouples in conjunction with a datalogger. A total of six thermocouples monitored the temperatures of the ambient air (dry and wet bulb), the drying air, and the exhaust air (dry and wet bulb).

The drying-air temperatures and the stored-grain temperatures were stored on magnetic tape. Data treatment and manipulation were performed directly by means of tape and a digital computer.

The airflows were calculated from measured static-pressure data and from fan curves supplied by the fan and dryer manufacturers. The data were checked against standard ASAE static-pressure data for corn.

Liquid propane usage was estimated from the liquid propane tank gauge and later checked against the receipts received from the liquid propane supply company. Differences between the gas company receipts and the tank gauge readings were estimated at ±7% for an approximate 950 liters measurement. Liquid propane consumption for each individual batch or cycle (in-bin counterflow dryer) was taken as the daily average (liter/min) times the drying time.

Electricity usage was measured with a Kwh-meter supplied by the electrical power company.

Sample evaluation was performed using standard methods of measuring stress-cracks (Thompson & Foster, 1963). The 2,3,5-triphenyltetrazolium chloride color test (TZ test) was used to determine the percentage of viable kernels. The TZ test distinguishes between viable and dead tissues of the embryo on the basis of respiration rate in the hydrate state. The TZ test is widely recognized as an accurate means of estimating seed viability (Copeland, 1976). Breakage tests were conducted employing a newly developed USDA method (Miller et al., 1979).

5. RESULTS AND DISCUSSION

5.1 Ambient and Drying Conditions

5.1.1 High-Temperature Phase

Table 6 and Tables 7 and 8 contain the daily average ambient and drying conditions for the cross-flow batch dryer (fall 1978 and 1979) and for the in-bin counterflow dryer (fall 1978 and 1979), respectively. Only the batches or cycles (in-bin counterflow) for which a complete set of data was collected are described in the tables. The data presented in Table 6 were averaged from the daily operation. As the drying season progressed from November 3, 1978 (ave. 1) to November 10, 1978 (ave. 7), the initial moisture content was substantially reduced (from 28.6% to about 24% wb). The high ambient temperature and the low relative humidity during those days highly contributed to the efficient field drying. By November 10, 1978, the 4.9 min. of drying time for the corn from ave. 7 indicates that before being dumped into the combination drying bin, the corn was only warmed up. The corn from ave. 8 and ave. 9 (control batches) was dried on November 7, 1978, and November 10, 1979, when the initial moisture contents were 26% and 35.7% wb, respectively. Table 6 also indicates the effect of the initial and final moisture contents on the drying time and energy consumption for the crossflow batch dryer. As a result of schedule pressures and instrumentation failure, only one complete batch-drying test is reported for 1979 (Table 6, ave. 9).

Table 6: Ambient and drying conditions for the experimental tests (daily averages) in Bellaire, Michigan, November 1978, for the cross-flow batch dryer without cooling.

Test Number[a]	Ambient Rel. Hum. %	Air Temp. C	Drying Temp. C	Moisture Inlet % wb	Content Outlet % wb	Grain Temp. C	Drying Time Min.	Liquid Propane Liters	Elect. Energy Kwh	Total Energy KJ
Ave. 1 (10)	55	17.2	91.0	28.6	22.9	18.7	29.6	41.6	6.8	1092136
Ave. 2 (10)	68	10.6	94.4	28.6	22.9	18.0	26.0	49.2	6.2	1310331
Ave. 3 (4)	81	2.8	99.4	27.9	23.0	8.0	21.3	41.2	5.7	1573667
Ave. 4 (4)	58	4.8	86.6	26.9	22.9	8.1	17.2	32.5	5.7	884271
Ave. 5 (9)	60	12.6	98.1	24.7	22.7	12.5	10.3	19.4	3.6	449749
Ave. 6 (15)	71	11.1	103.8	24.0	20.0	11.6	18.4	34.4	4.6	967750
Ave. 7 (6)	82	9.1	100.0	24.8	23.5	11.0	4.9	9.0	2.4	532765
Ave. 8 (2)	50	6.8	100.5	26.0	15.5	10.0	60.0	104.0	12.0	2712352
Ave. 9 (1)[b]	60	12.5	99.4	35.7	18.3	12.2	95.0	149.8	20.8	3918470

[a]The value in parentheses is the number of replications.

[b]November 1979 data.

For the grain to be final-dried in the in-bin dryeration, natural-air, and low-temperature combination drying systems, the cooling cycle of the high-temperature batch dryer was not operated. The in-bin dryeration system requires that the corn be at a high temperature for adequate operation. The two combination drying systems also had the advantage of the high sensible heat carried by the uncooled corn, which improved the drying efficiency of the dryer. As will be shown later in this chapter, by eliminating the cooling operation, the drying capacity of the cross-flow dryer was substantially increased.

Tables 7 and 8 contain the ambient and drying condition data for the in-bin counterflow system for the 1978-1979 season (cycles 1 to 18) and the 1979-1980 season (cycles 19 to 34). The drying time in Tables 7 and 8 refers to the time between two consecutive cycles after cycle (0) or the initial cycle had been unloaded. The unusually high initial moisture content for the corn in the 1979 season (Table 8, cycles 19 to 27 and ave. 9 in Table 6) was a result of the frost that occurred during the first week of October, which required early harvesting of part of the corn (Table 8, cycles 19 to 27), 15 days before the predicted starting harvest date.

In the in-bin counterflow "Shivvers system" the drying occurs in two steps. In the first step the corn is dried to a low moisture content such as 18%, and the drying is completed in the aeration bin. During the 1978-1979 season, the final drying for the in-bin counterflow

Table 7: Ambient and drying conditions for the experimental tests (in-bin counterflow) in Bellaire, Michigan, November 1978.

Cycle No.[a]	Ambient Rel. Hum. %	Air Temp. C	Drying Temp. C	Moisture Content Inlet % wb	Moisture Content Outlet % wb	Drying Time Min.[b]	Liquid Propane Liters	Elect. Energy Kwh	Total Energy KJ	Static Pressure CM H_2O
1	92	14.5	66.3	25.4	15.3	25.0	29.1	5.0	765365	7.8
2	93	13.9	69.2	25.0	17.3	20.0	23.3	4.0	612292	6.3
3	99	13.1	72.0	25.0	18.0	20.0	23.3	4.0	612292	6.8
4	99	12.1	69.0	25.0	17.9	20.0	23.3	4.0	612292	7.1
5	99	11.9	71.4	25.0	18.6	20.0	23.3	4.0	612292	7.3
6	95	11.1	68.5	27.2	18.8	20.0	23.3	4.0	612292	6.3
7	96	10.9	68.4	27.2	18.6	20.0	23.3	4.0	612292	5.8
8	97	10.0	70.0	27.2	18.4	20.0	23.3	4.0	612292	5.0
9	59	7.7	67.8	27.4	18.6	25.0	28.8	5.0	758571	8.1
10	70	7.9	67.7	27.4	19.6	20.0	23.0	4.0	606468	8.1
11	55	8.2	67.9	27.4	20.3	20.0	23.0	4.0	606468	7.3
12	56	8.1	65.7	27.4	19.1	25.0	28.8	5.0	758571	8.8
13	58	7.7	67.4	27.4	19.8	25.0	28.8	5.0	758571	9.6
14	60	6.8	65.6	27.0	19.2	25.0	28.8	5.0	758571	9.6
15	66	6.5	67.6	27.0	18.5	30.0	29.9	6.0	790319	10.1
16	69	4.9	67.5	27.0	19.6	25.0	24.9	5.0	658599	10.4
17	73	3.9	65.5	27.0	17.5	25.0	24.9	5.0	658599	9.3
18	54	5.2	65.5	27.0	18.8	25.0	24.9	5.0	658599	9.1

[a]Refers to the layer that is dropped from the dryer into the auxiliary bin.

[b]Time between two consecutive cycles.

system had been completed by December 7, 1978, after 590 hours of fan operation. Because of the frost that occurred on the first day of October 1979, the corn from cycles 19 to 27 was harvested and dried early to avoid being spoiled in the field. The second drying phase (from about 18.5 to 15.5% wb) was completed during the remainder of October with the aeration bin less than half full (approximately 20 tons). Because of the low moisture content (14.7% average) when the corn was dumped into the aeration bin (cycles 28 to 34), the second drying phase is not considered for the 1979-1980 season.

5.1.2 Low-Temperature Phase

The corn from ave. 1, ave. 5, four batches from ave. 7 (Table 6), and one unreported batch was put in the natural-air combination drying bin. The average moisture content was 23.1% wb, with a standard deviation of SD = 1.31. The low-temperature combination drying bin was loaded with corn from ave. 2, ave. 3, ave. 4, two batches from ave. 7 (Table 6), and four unreported batches. The average moisture content of the corn was 23% wb, with a standard deviation of SD = .76. The initial moisture content of the corn when placed in the dryeration bin (1978 season) was higher than planned due to the inaccuracy of the moisture tester. The bin was loaded with corn from ave. 6 (Table 6) and four unreported batches; the average moisture content was 20% and the standard deviation SD = .53.

For the natural-air and low-temperature combination drying systems, the fan was turned on as soon as the third batch (approximately 11.8 m^3) of the hot corn was placed in the bins. For the in-bin dryeration system, the fan was turned on after a 10-hour tempering period with approximately 58 m^3 of corn in the bin.

Drying in the natural-air and low-temperature drying bins was interrupted in the second week of December 1978, when the average ambient-air temperature had fallen below 2°C. In the middle of April 1979, the fans were restarted for 10 days to complete the drying process.

In the 1978-1979 season, the fan in the natural-air bin operated 884 hours; the fan in the low-temperature bin operated 794 hours. For the in-bin dryeration drying (1978-1979 season), the fan operated 448 hours and drying was completed by December 15, 1978.

5.2 Product Quality

The results of the analysis of the wet corn and dried corn samples, which correspond to the data in Tables 6 and 7 (cycles 1 to 18), are shown in Tables 9 and 10, respectively. Except for the breakage test for the high-temperature drying technique, the quality test was not performed for the 1979-1980 season. The final grain quality for each drying technique is presented in Table 11, in which the corn breakage test determined according to the new USDA method (Miller et al., 1979) is presented.

A careful examination of Tables 9, 10, and 11 clearly shows that the quality of the end-product is substantially affected by the drying procedure, as was previously found by Thompson and Foster (1963), Peplinski et al. (1975), Shove (1978), and Gustafson et al. (1978). The in-bin counterflow dryer produced dried corn that was

Table 8: Ambient and drying conditions for the experimental tests (in-bin counterflow) in Bellaire, Michigan, November 1979.

Cycle No.[a]	Ambient Rel. Hum. %	Air Temp. C	Drying Temp. C	Moisture Content Inlet % wb	Moisture Content Outlet % wb	Drying Time Min.[b]	Liquid Propane Liters	Elect. Energy Kwh	Total Energy KJ	Static Pressure CM H_2O
19	98	12.7	66.6	37.0	18.6	87.0	71.3	17.4	1892232	11.9
20	98	12.1	65.5	37.8	18.8	60.0	49.2	12.0	1304987	11.4
21	90	12.1	65.5	37.8	16.8	68.0	55.7	13.6	1478662	10.9
22	85	12.1	65.5	37.8	15.7	91.0	74.6	18.2	1979555	10.6
23	70	14.3	65.5	37.8	19.5	57.0	46.7	11.4	1239737	9.9
24	70	14.3	64.3	37.8	18.7	73.0	59.8	14.6	1588058	10.1
25	73	13.2	65.5	37.8	18.7	60.0	49.2	12.0	1304987	9.6
26	78	12.7	66.6	37.8	19.7	63.0	51.6	12.6	1370237	9.6
27	85	8.8	67.7	37.8	18.2	57.0	46.7	11.4	1239737	8.8
28	98	10.0	71.0	34.0	14.9	60.0	50.2	12.0	1331193	10.4
29	100	8.8	70.0	34.0	14.9	65.0	54.4	13.0	1442531	8.8
30	100	3.2	71.0	30.8	13.5	73.0	59.5	14.6	1479323	13.4
31	100	3.2	72.7	30.8	14.2	67.0	54.6	13.4	1449794	12.9
32	100	3.2	71.0	30.8	14.7	73.0	59.5	14.6	1479323	14.4
33	100	3.2	72.1	30.8	14.8	68.0	55.4	14.6	1474498	13.4
34	100	1.0	71.0	30.8	15.9	67.0	54.6	13.4	1449794	12.7

[a]Refers to the layer that is dropped from the dryer into the auxiliary bin.

[b]Time between two consecutive cycles.

Table 9: Average grain quality parameters for the crossflow batch dryer, 1978 drying season.

Test No.	Moisture %wb In	Moisture %wb Out	Stress-Cracks[a]	% Whole Kernels In	% Whole Kernels Out	Viability % In	Viability % Out	BCFM In	BCFM Out	Test Weight In	Test Weight Out
Ave. 1	28.4	22.9	4.6	96.5	97.0	77.8	39.0	0.0	0.0	52.0	54.0
Ave. 2	28.6	22.9	4.2	96.9	97.4	82.9	38.4	0.0	0.0	52.0	54.0
Ave. 3	27.9	23.0	3.7	96.5	96.6	74.0	40.0	0.0	0.0	53.0	53.7
Ave. 4	26.9	22.9	4.0	96.5	96.6	85.5	42.0	0.0	0.0	53.6	54.2
Ave. 5	24.7	22.7	1.5	96.9	97.2	92.4	52.0	0.0	0.0	53.3	52.7
Ave. 6	24.0	20.0	8.9	96.7	96.5	96.3	34.3	0.0	0.0	53.5	53.9
Ave. 7	24.8	23.5	2.9	95.7	95.7	89.3	59.0	0.0	0.0	54.3	53.5
Ave. 8	26.0	15.5	87.3	96.8	96.6	86.0	8.0	0.0	0.0	54.0	55.0
Ave. 9	35.7	18.3	76.0	96.3	97.0	..	..	1.0	1.0	50.0	55.5

[a]The initial stress-cracks percentage equals zero.

Table 10: Grain quality parameters for the in-bin counterflow dryer, 1978 drying season.

Test No.	Moisture %wb In	Moisture %wb Out	Stress-Cracks[a]	% Whole Kernels In	% Whole Kernels Out	Viability % In	Viability % Out	BCFM In	BCFM Out	Test Weight In	Test Weight Out
1	25.11	15.3	36.0	95.6	96.6	90.5	68.0	0.0	0.4	52.7	56.0
2	25.0	17.3	32.0	95.6	95.0	90.5	64.0	0.0	0.4	52.7	56.0
3	25.0	18.0	38.0	95.6	96.8	90.5	72.0	0.0	0.0	52.7	55.0
4	25.0	17.9	50.0	95.6	95.3	90.5	68.0	0.0	0.0	52.7	56.0
5	25.0	18.6	26.0	95.6	94.9	90.5	84.0	0.0	0.4	52.7	56.0
6	27.2	18.8	46.0	96.8	95.0	90.0	60.0	0.0	0.5	53.0	55.0
7	27.2	18.6	34.0	96.8	95.2	90.0	78.0	0.0	0.6	53.0	55.0
8	27.2	18.4	38.0	96.8	95.0	90.0	64.0	0.0	0.4	53.0	55.0
9	27.4	18.6	30.0	95.7	95.0	90.0	68.0	0.0	0.0	53.7	55.0
10	27.4	19.6	52.0	95.7	96.0	90.0	62.0	0.0	0.4	53.7	56.0
11	27.4	20.3	34.0	95.7	95.6	90.0	80.0	0.0	0.0	53.7	56.0
12	27.4	19.1	60.0	95.7	94.3	90.0	44.0	0.0	0.0	53.7	57.0
13	27.4	19.8	38.0	95.7	95.3	90.0	44.0	0.0	0.0	53.7	57.0
14	27.0	19.2	50.0	94.6	96.2	90.0	52.0	0.0	0.0	54.0	56.0
15	27.0	18.5	46.0	94.6	96.0	90.0	52.0	0.0	0.4	54.0	56.0
16	27.0	19.6	32.0	94.6	96.9	90.0	64.0	0.0	0.6	54.0	56.0
17	27.0	17.5	86.0	94.6	96.3	90.0	..	0.0	..	54.0	56.0
18	27.0	18.8	50.0	94.6	92.0	90.0	..	0.0	..	54.0	56.0

[a]The initial stress-cracks percentage equals zero.

less susceptible to damage than that produced by the cross-flow batch dryer. Of the 87.3% kernels with stress-cracks dried in the automatic batch dryer (Table 11), 28.5% were checked, whereas only 7.0% of the 64% stress-cracked kernels dried in the in-bin counterflow dryer exhibited those characteristics. This is reflected in the 46.3% breakage test for the batch dryer compared to 29.0% for the in-bin counterflow dryer.

When the batch dryer was used in combination with the low-temperature, natural-air, and in-bin dryeration drying systems, the number of kernels with stress-cracks and the breakage test percentages were substantially improved. This agrees with Gustafson et al. (1978), who stated that the final moisture content for high-temperature drying above 18% does not appear to cause a significant increase in breakage susceptibility. The average breakage test results in 1979 were 28.2% and 33.1% for the in-bin counterflow and batch dryer, respectively. The difference between the two drying techniques was smaller in the 1979-1980 than in the 1978-1979 tests. The final moisture contents, 18.5% and 14.7% wb for the batch and in-bin counterflow dryer, respectively, are the most probable cause of the smaller difference in 1979-1980.

When the batch dryer is part of the drying system, the change in viability is substantially higher than for the in-bin counterflow dryer. The high drying-air temperature used for the batch dryer accounts for this difference. Even though the "residence time" for in-bin dryeration drying is only slightly lower than that for the two combination drying techniques (high-temperature phase), the decrease in viability for in-bin dryeration was substantially higher (Table 11). The long tempering time at high temperatures during the dryeration process might be a reasonable explanation for the difference. This explanation agrees with Gustafson et al. (1978), who found that high "time-temperature drying" has a very high negative effect on germination. Final test weight (Table 11), percentage of whole kernels, and BCFM (Tables 9 and 10) were not affected by the different techniques. Auger adjustment for the in-bin counterflow system might account for the slight variation in BCFM (Table 10) for this system for the 1978 tests.

All grain dried with the natural-air and low-temperature combination drying, in-bin dryeration, in-bin counterflow, and automatic batch drying systems was sold commercially as No. 2 corn.

5.3 Effect of the Weather and Design Parameters on the Drying Procedure

Compared to the 1979-1980 season, the 1978-1979 drying tests benefited from excellent weather conditions during the harvesting and subsequent drying season. This partially accounts for the favorable results of the two combination drying techniques and the in-bin dryeration system in 1978-1979. The high-temperature batch drying and in-bin counterflow drying systems are not affected as much by weather changes.

The design values for the airflow rate in the two combination drying systems were relatively high (Bakker-Arkema et al., 1978). Simulation (Bakker-Arkema et al., 1976) suggests that airflows of about 1.0 and 0.8 $m^3/min/m^3$ would have been more energy efficient during the 1978-1979 season for the natural-air and low-temperature bins, respectively, than the design values of 2.0 and 1.6 m^3 of air per cubic meter of grain. However, in less favorable weather (fewer drying days, humid, and with periods of high temperature) as occurred during the 1979-1980 drying season, the airflow rates were insufficient to prevent mold growth in the top layer of the natural-air bin.

The average moisture content of the corn at the end of the 1978-1979 drying season in the two combination drying bins was lower than planned because of the need to lower the moisture content in the top layer in the two bins to at least 16.5%. By the time this occurred, the bottom layers were overdried. This was especially true for the high-temperature/low-temperature (electric heat) combination-drying bin, in which the moisture content of the bottom grain layer had reached 11.6% by the time the fan was turned off. To eliminate the overdrying problem, a one-screw stirrer was added to the low-temperature system for the 1979-1980 season.

The relatively warm ambient conditions that prevailed in the 1978-1979 season during the loading, tempering, and final drying of the grain in the in-bin dryeration bin aided in keeping the condensation along the bin walls to a minimum. No visible mold or any kind of odor was detected on the grain next to the walls or on the top layer when the bin was unloaded after winter storage. As previously stated, weather conditions play a major role when natural and low-temperature air is used. Extra labor is required for weekly inspections since automatic humidistats are not dependable, requiring frequent calibration. Because very little drying occurs when the temperature drops below freezing, the fans should be shut off when the exhaust-air temperature is below 1.6°C.

In-bin counterflow and automatic batch drying systems are much less dependent on the weather conditions and do not require the same level of operator attention and expertise as do natural-air and low-temperature drying techniques. If the high-temperature system functions properly and the dryers are sized correctly according to harvesting rate, grain drying should not create any problems or bottlenecks. The unusually high initial moisture content in the 1979 harvesting season did not cause any major problems during the drying operation using the batch dryer or the in-bin counterflow dryer. Because no shelter was provided for the automatic batch dryer, drying during periods of heavy rain was not possible. The same problem did not affect the in-bin counterflow dryer, in which the corn being dried is completely protected.

5.4 Drying Efficiency and Dryer Performance

5.4.1 Overview

Drying systems are commercially sold with rating tables listing crop dryer capacity. However, knowledge of the energy efficiency and operating characteristics is needed if farmers are to select drying systems intelligently. Dryer capacities are usually quoted in wet or dry bushels of corn being dried and cooled for 10 or 5 points of moisture removed, 25-15% and 20-15%, respectively. To show more favorable statistics for their dryers, some manufacturers use the wet bushel for rating dryer capacities, and in some instances the loading and unloading times are not taken into account in rating batch dryers (see Table 4). The bushels are calculated by dividing the wet or dry weight in pounds by 56, regardless of the test weight (weight per bushel) or grain moisture content. Rating grain dryers by wet weight per unit of time (e.g., tons per hour) would result in less confusion (Bakker-Arkema et al., 1978). In the past five years, the cost of energy sources such as liquid propane, natural gas, and electricity has substantially increased. Thus, the need for energy-efficiency information becomes more important as nonrenewable energy sources are running out and as various countries face shortages due to political pressures.

5.4.2 Energy Consumption and Operating Costs

Table 11 contains the general energy-consumption results and drying efficiency of the five drying tests performed during the 1978 harvesting season at the Kalchik Farms. The table also shows the actual operating costs and quality for each technique. Natural-air and low-temperature combination drying systems have much lower energy (KJ/Kg of water removed) requirements than the two high-temperature drying systems. Besides being highly dependent on the ambient conditions, the two combination techniques are more dependent on electrical energy, which has a substantially higher cost per kilojoule than any other conventional source of energy. The final moisture contents for natural-air and low-temperature combination drying (Table 11) are far below the desired 15.5% moisture content (wb).

Table 11: Actual energy consumption, operating costs (1979 prices), and corn quality parameters for six alternative corn-drying methods at the Kalchik Farms, Bellaire, Michigan, fall 1978.

Drying Technique	Moisture Content			Amount Dried	Electricity	Propane	Drying Efficiency	Total Energy,[a] Propane Equivalent	Energy Costs[b]	Stress-cracks	Breakage Tests[c]	Test Weight	Viability Changes[d]
	Initial	Intermediate %,wb	Final %,wb	Tons	Kwh	Liters	KJ/Kg H_2O	Liter/acre	$/ton	%	%	lb/bu	%
Natural air	26.2	23.1	14.4	60.2	3415	681	3173	53.7	4.26	2.8	11.9	55.0	34.0
Low-temperature	27.5	23.0	13.8	60.0	5095	1022	4028	81.0	7.44	3.4	13.1	54.5	40.0
In-bin dryeration	24.0	20.0	15.6	..	595	708	3530	43.1	2.44	9.0	13.8	55.0	76.0
In-bin counterflow	26.4	18.3	16.3	62.0	818	1419	4699	63.3	3.64	64.0	29.0	56.3	25.0
Automatic batch	26.0	..	15.5	7.5	36	310	6584	118.5	5.40	87.3	46.3	55.5	78.0

[a]Based on 2.8 ton/acre.

[b]Based on 6.2¢/Kwh and 11.9¢/liter of propane; labor and other costs not included.

[c]Breakage test determined at 10%, wet basis and 24°C (% passing through a .48 cm diameter round-hole seive).

[d]Viability change is defined as the change in the viability of the grain before and after drying.

To allow a better comparison, the standardized energy consumption and operating costs for each technique are given in Table 12. The table was generated taking into consideration the experimental data (1978-1979 season). For each drying technique, the corn is dried from 26% to 15.5% wb. In Table 11, the electrical energy usage is transformed into propane equivalent, and the total energy consumption is given in terms of liters of propane per acre. Tables 11 and 12 suggest that in-bin dryeration and in-bin counterflow drying appear to hold the most promise. In terms of cost, the systems are superior, and their energy requirements are also substantially lower than those of conventional high-temperature batch-drying systems. The lower operating cost and the excellent drying efficiency, in comparison to other high-temperature drying techniques, make in-bin counterflow drying a very attractive drying method on small and medium-sized farms. However, energy efficiency and operating cost are not the only points to be considered in adopting a particular system; the management and economics of each system, to be presented later in this chapter, are equally important.

5.4.3 Comparison of the Operational Characteristics of the Batch and In-Bin Counterflow Dryers

The energy efficiency and drying capacity of the Farm-Fans automatic batch dryer model AB-8B increased substantially when the corn was dried in the combination drying system to approximately 23% moisture content rather than to 15.5% moisture content. The energy efficiency improved from 7507 KJ per Kg of water removed to 5750 KJ/Kg, and the drying capacity improved (excluding cooling time) from

Table 12: Standardized energy consumption and operating costs (1979 prices) for five alternative corn-drying methods in Michigan, based on the results of the Kalchik Farms tests, fall 1978, in Bellaire, Michigan.

Drying Techniques	Electricity[a] Kwh	Propane Liters	Electricity Kwh/acre	Propane Liter/acre	Energy Drying Efficiency	Total Energy,[b] Propane Equiv. Liter/acre	Drying Cost[c] $/ton
Natural air (26-23-15.5%)MC	3156	670	138.8	29.5	3227[d]	49.2	4.44
Low-temperature (26-23-15.5%)MC	4449	670	195.0	29.5	3756[d]	57.1	5.68
In-bin dryeration (26-20-15.5%)MC	867	1035	38.2	57.5	4140[d]	62.8	3.40
In-bin counterflow (26-18-15.5%)MC	952	1434	41.9	63.2	4548	69.2	3.72
Automatic batch (26-15.5%)MC	306	2653	13.5	116.5	6589	118.4	5.44

[a]Based on 63.5 tons (55 lb/bushel) and initial MC of 26.0% wb and final MC of 15.5%.

[b]Based on 2.8 ton/acre.

[c]Based on 6.2¢/Kwh and 11.9¢/liter of propane; labor and other costs not included.

[d]Energy efficiency of high-temperature drying phase is 6228 KJ/Kg H_2O.

approximately 2.3 to 3.8 tons of dry corn per hour (Table 13). The airflow in the batch dryer used in the test was relatively high (at static pressure of 7.6 cm of H_2O, approximately 104 $m^3/min/m^3$ of grain for both the drying and the cooling phase).

The batch dryer under consideration has a high drying rate (75 min. per batch for drying and cooling in drying from 26 to 15.5% wb as compared to 120 to 180 min. for the average column-batch dryer) (Brooker et al., 1974). The high drying/cooling rate clearly explains the poor energy efficiency, higher percentage of stress-cracks (Thompson & Foster, 1963), and lower degree of germination (Copeland, 1976) for the high-temperature batch dryer as compared to the in-bin counterflow dryer.

The exhaust air of the crossflow batch dryer is plotted against drying time in Figures 20, 21, and 22. Because the exhaust air for the in-bin counterflow "Shivvers system" is always saturated, a similar figure for that dryer is not presented. Figures 20 and 21 represent one typical batch-drying run (26 to 15.5%) and one typical batch for the in-bin dryeration test (high-temperature phase), respectively, during the 1978-1979 season. Figure 22 is plotted with data from a typical batch-drying run (35.7 to 18.3%) during the 1979-1980 season, in which cooling is included. Only the first 30 minutes of the 75-minute batch duration are plotted in Figure 20. Figures 21 and 22 are plotted for the total duration of the batches. The low drying efficiency for the batch dryer can be understood by considering Figures 20 and 22, in which the exhaust-air temperature after 23-24 min. (Figure 20) and 44-45 min. (Figure 22) starts to increase rapidly (low relative humidity and high temperature). When Figure 21 is compared with Figures 20 and 22, it clearly shows that the dryer efficiency is improved when used with dryeration or combination drying. For the in-bin dryeration system (24-20% wb), the high-temperature phase stopped before the exhaust-air temperature started to increase (Figure 21). The dryer efficiency in this case was 6071 KJ/Kg of water removed. In Figure 20, the time of 100% relative humidity is approximately 15 min. and the drying efficiency 7521 KJ/Kg, whereas in Figure 22 the time of 100% relative humidity was much longer (32 min.). In this case, the drying efficiency was substantially improved (3796 KJ/Kg water removed). Thus, drying efficiency for a batch dryer is directly related to the time the exhaust air has 100% relative humidity.

In contrast to the batch dryer, the in-bin counterflow system shows higher energy-efficiency characteristics; if a sufficient bed depth (above .9 m) is maintained, saturated exhaust air is guaranteed.

In addition to the disadvantage of its high moisture-content differential across the columns, the batch dryer studied had relatively poor outlet grain-mixing characteristics, as shown in Figure 23, in which the moisture content of the samples when plotted against the time the samples were taken shows a high degree of variation as the dryer is unloaded. Considering that the moisture-content differential across the column is minimized as unloading progresses, the only reasonable cause for the observed variation is the high moisture-content gradient along the column due to automatic refilling as

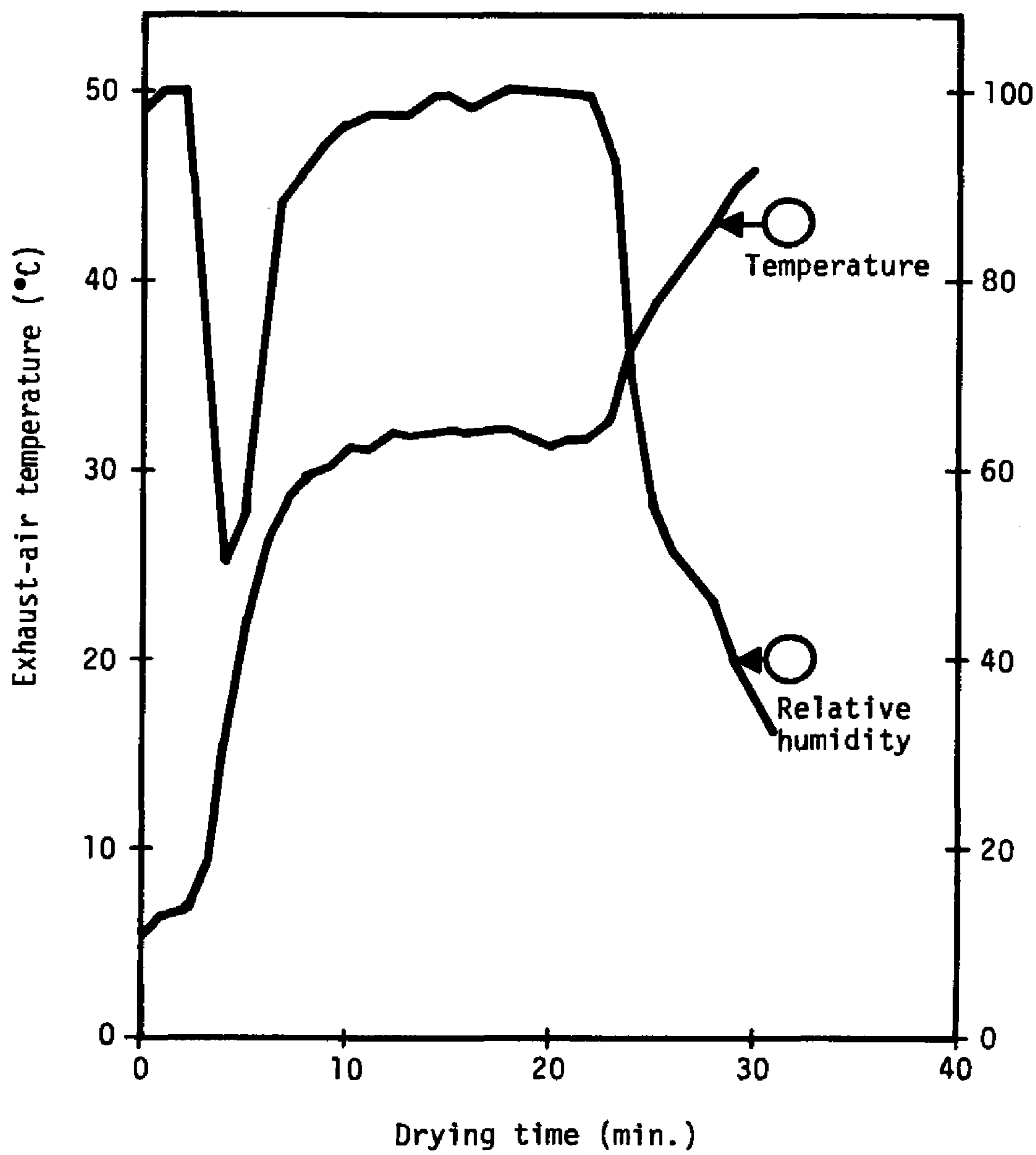


Figure 20. Exhaust-air relative humidity and temperature versus drying time for the batch dryer drying from 26 to 15.5% wb.

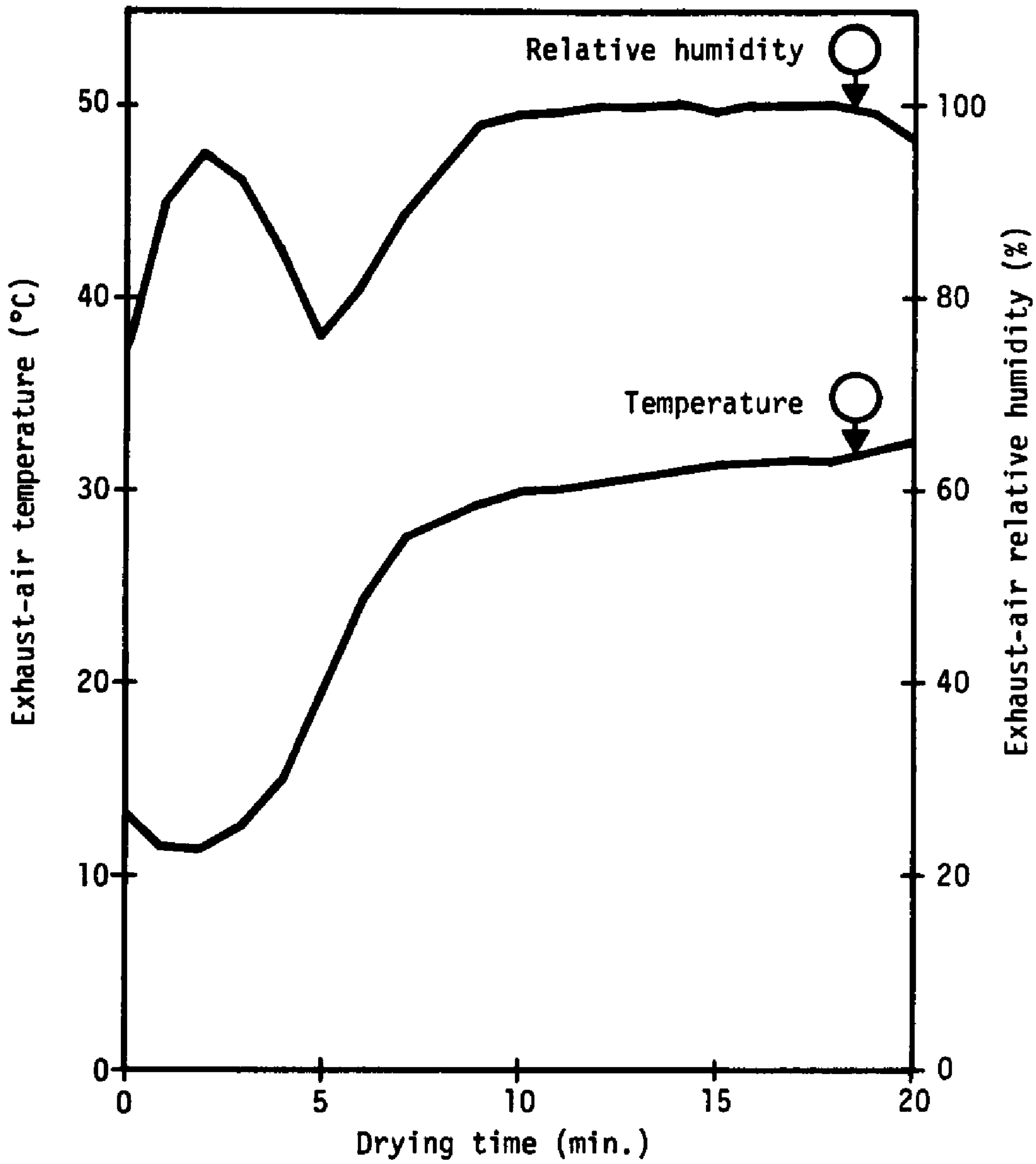


Figure 21. Exhaust-air relative humidity and temperature versus drying time for the batch dryer drying from 24 to 20% wb.

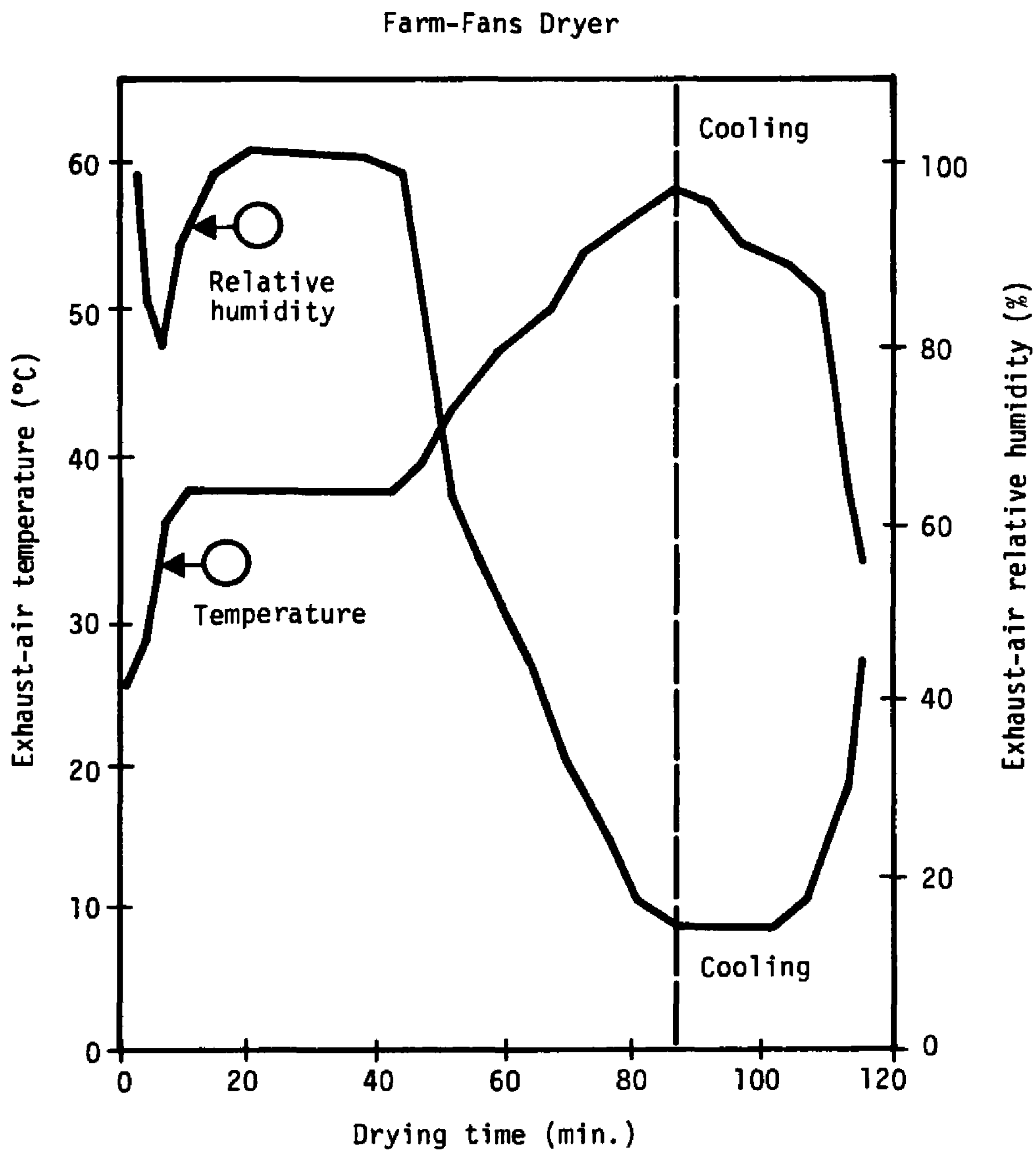


Figure 22. Exhaust-air relative humidity and temperature versus drying time for the batch dryer drying from 35.7 to 18.3% wb.

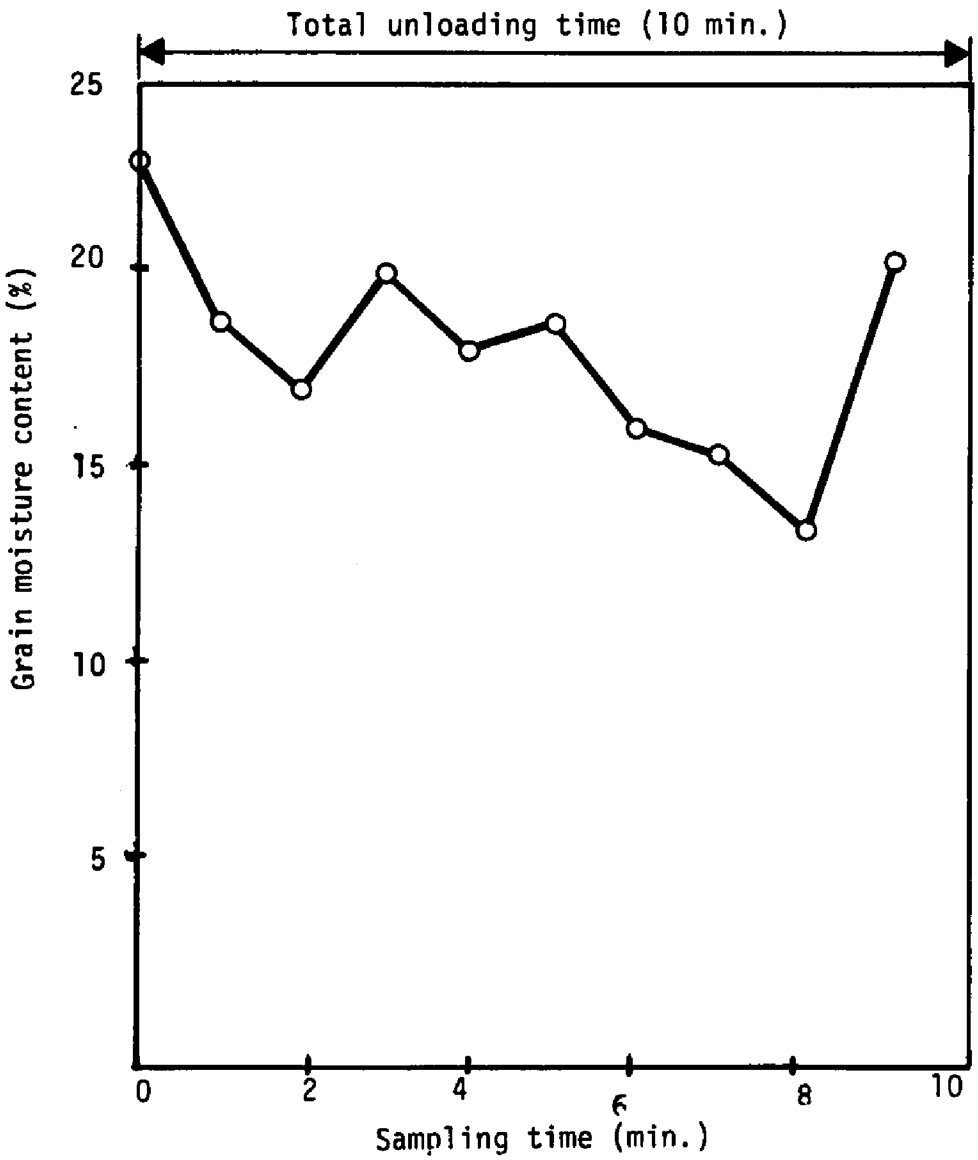


Figure 23. Variation in the final grain moisture content with regard to the sampling time for the batch dryer under consideration.

shrinkage occurs. The moisture variation as unloading progresses poses two major problems: (a) an error in the moisture determination due to sampling procedure, and (b) the small amount of high-moisture-content grain in the mass of dried corn may cause serious deterioration problems during the storage period.

Despite the very good energy efficiency shown by the in-bin counterflow dryer as compared to the batch dryer (see Tables 13, 14, and 15), the energy losses are still high. Average heat losses of about 25% are estimated. To illustrate, the heat losses for cycle 28, Table 8, are calculated. For that particular cycle, the temperature (T_1) inside the plenum chamber was 71°C, the airflow rate (F) 9.60 m^3/m^2/min, outside air temperature (T_2) 10°C, drying time (t) 1 hour, air density (v) 1.02 Kg/m^3, specific heat of air (c) 1 KJ/Kg°C, and bin floor area (A) 23.59 m^2. Thus:

$$m = A \cdot F \cdot t \cdot v = 9.60 \times 23.59 \times 60 \times 1.02 = 13{,}859 \text{ Kg/hr},$$

$$q = m \cdot c\ (T_1 - T_2) = 13{,}859 \times 1 \times (71 - 10) = 845{,}435 \text{ KJ/hr}$$

To maintain the above condition, the measured energy usage was 1,195,968 KJ/hr. The percentage of heat loss is:

$$\%q = \frac{ME - UE}{ME} \times 100$$

where: %q = percentage of heat loss,

ME = measured energy, and

UE = usable energy

$$\%q = 100 \times (1{,}195{,}968 - 845{,}435) \div 1{,}195{,}968 = 29.3\%$$

or equivalent to approximately 12.8 liters of liquid propane.

Table 13: Average energy from liquid propane consumption, drying efficiency, drying time, and dryer capacity as calculated by the drying model and as measured in the field tests with the batch dryer.

Test No.	Moisture Content Initial	Moisture Content Final	L. Propane (in KJ) Calc.	L. Propane (in KJ) Obs.	Drying Eff. Calc.[a]	Drying Eff. Obs.[a]	Drying Time Calc.[b]	Drying Time Obs.[b]	Tons/Hour Calc.	Tons/Hour Obs.
Ave. 1	28.6	22.9	1230104	1067660	5547	4814	29.7	29.6	3.48	3.49
Ave. 2	28.6	22.9	1281999	1261780	5796	5690	28.1	26.0	3.60	3.76
Ave. 3	27.9	23.0	1218548	1057954	5985	5219	23.6	21.9	3.98	4.13
Ave. 4	26.9	22.9	852313	776480	6845	6694	17.8	17.2	4.58	4.66
Ave. 5	24.7	22.7	407163	431706	5384	6603	8.7	10.3	6.04	5.72
Ave. 6	24.0	20.0	854031	883246	5857	6118	16.8	18.4	4.70	4.50
Ave. 7	24.8	23.5	233956	232944	4918	4998	4.8	4.9	6.99	6.94
Ave. 8	26.0	15.5	3047958	2669150	7521	6584	56.0	60.0	2.27	2.31
Ave. 9	35.7	18.3	4050728	3843576	5491	5207	85.7	95.0	1.64	1.57

[a] KJ/Kg of water removed.

[b] Drying time in minutes.

Table 14: Energy consumption, drying efficiency, water removed, and dryer capacity as calculated by the drying model (1978 data), with the in-bin counterflow dryer.

Cycle No.	Moisture Content Initial	Moisture Content Final	Propane KJ	Elect. Kwh	Drying Time	Propane Equiv.[a]	Drying Eff. KJ/Kg H_2O	Water Removed[b]	Dryer Capacity[c]
1	25.40	15.30	1323094	6.6	32.2	52.5	4373	303	2.3
2	25.00	17.30	1562281	6.0	21.7	61.7	4581	341	3.5
3	25.00	18.00	1598099	6.2	19.5	63.1	4649	344	3.9
4	25.00	17.90	1544157	6.3	20.5	61.1	4655	332	3.7
5	25.00	18.60	1566279	6.4	18.6	61.9	4743	330	4.0
6	27.20	18.80	1655043	6.0	23.2	65.3	4721	351	3.2
7	27.20	18.60	1726278	5.7	22.9	68.1	4732	365	3.3
8	27.20	18.40	1972439	4.9	20.5	77.6	4738	417	3.7
9	27.40	18.60	1504398	6.6	26.4	59.6	4636	325	2.8
10	27.40	19.60	1496888	6.6	24.6	59.3	4857	308	3.0
11	27.40	20.10	1587745	6.4	21.0	62.8	4689	339	3.6
12	27.40	19.10	1357039	6.8	28.0	53.8	4702	289	2.7
13	27.40	19.80	1323811	7.0	26.8	52.6	4708	281	2.8
14	27.00	19.20	1303854	7.0	29.3	51.8	4967	262	2.6
15	27.00	18.50	1314764	7.1	31.0	52.2	4857	271	2.4
16	27.00	19.60	1320104	7.1	28.0	52.4	5056	261	2.7
17	27.00	17.50	1408334	6.9	34.0	55.9	5108	276	2.2
18	27.00	18.80	1406744	6.9	27.8	55.8	4836	291	2.7

[a]Liters per hour

[b]Kilos per hour.

[c]Tons per hour.

Table 15: Energy consumption, drying efficiency, water removed, and dryer capacity as calculated by the drying model (1979 data), with the in-bin counterflow dryer.

Test No.	Moisture Content Initial	Moisture Content Final	Propane KJ	Elect. Kwh	Drying Time	Propane Equiv.[a]	Drying Eff. KJ/Kg H_2O	Water Removed[b]	Dryer Capacity[c]
19	37.80	18.60	996519	7.2	85.5	39.8	3978	250	0.8
20	37.80	18.80	1038686	7.2	79.0	41.5	3876	268	0.9
21	37.80	16.80	1079483	7.1	83.6	43.1	3852	280	0.9
22	37.80	15.70	1092199	7.1	84.7	43.5	3754	291	0.9
23	37.80	17.00	1147395	7.0	76.2	45.7	3772	304	1.0
24	37.80	18.70	1075912	7.1	73.4	42.9	3709	290	1.0
25	37.80	18.70	1171801	7.0	67.5	46.6	3715	315	1.1
26	37.80	19.70	1195200	7.0	65.9	47.5	3906	306	1.1
27	37.80	18.20	1387667	6.8	62.8	55.0	3989	348	1.2
28	34.00	14.90	1262177	7.1	64.9	50.2	4041	312	1.1
29	34.00	14.90	1424810	6.8	57.9	56.5	4070	350	1.3
30	30.80	13.50	1099096	7.2	72.8	43.8	4490	245	1.0
31	30.80	14.20	1173104	7.2	66.9	46.7	4591	255	1.1
32	30.80	14.70	1013782	7.1	71.0	40.5	4526	224	1.0
33	30.80	14.80	1116928	7.2	67.2	44.5	4555	245	1.1
34	30.80	15.90	1203931	7.2	60.7	47.9	4767	252	1.2

[a]Liters per hour.

[b]Kilos per hour.

[c]Tons per hour.

Using conservative figures of 65 m^2 of exposed surface, 38°C temperature differential, convection heat transfer coefficients of 23 and 56 $w/m^2/hr\ °C$ (McAdams, 1954) for the outside and inside air, respectively, and ignoring the heat resistance due to conduction, the heat losses by convection can be estimated by:

$$q = \frac{\Delta T}{\frac{1}{Ah_1} + \frac{1}{Ah_2}}$$

where: ΔT = temperature differential between ambient and drying air (°C)

A = exposed surface (m^2)

q = heat loss by convection

h_1 = convection heat transfer coefficient for outside surface ($w/m^2\ °C$)

h_2 = convective heat transfer coefficient for inside surface ($w/m^2\ °C$)

$$q = \frac{38}{\frac{1}{65x23} + \frac{1}{65x56}}$$ = 40,270 w or approximately 5.6 liters of liquid propane per hour.

The plenum chamber area, concrete floor, unloading auger, fan-bin transition, high air-temperature leakage through the double wall space, and the less than 100% efficiency of the burner account for a large part of the total heat loss.

5.5 Experimental Versus Predicted Results

5.5.1 Model Validation

Using the ambient and drying conditions data from the tests conducted at Kalchik Farms (Tables 6, 7, and 8), Hukill's (1954) deep-bed drying model was used to predict the drying time and the other drying parameters for the in-bin counterflow ("Shivvers" system) and the cross-flow batch dryer (Farm Fans model AB-8B). Tables 13, 14, and 15 present the results of the analysis for the batch and in-bin counterflow dryer, respectively. The calculation of the drying time for a particular set of drying conditions in Table 7 is illustrated in Appendix D.

One way to compare the predicted results of a model with the experimental results is by using the graphical method. This procedure involves plotting the desired parameter as the abscissa and the predicted values of the parameter as the ordinate. If the plotted points fall along a 45° line passing through the origin, there is said to be a perfect correspondence between the predicted and observed values (Y = X). The deviation from this line can be measured by a regression coefficient, which measures the amount of change in one variable associated with a unit change in the other variable.

The observed drying times for the in-bin counterflow dryer (shown in Tables 7 and 8) are plotted against the calculated drying time (Tables 14 and 15) and results in Figure 24. The corresponding regression analysis is presented in Table 16. The observed and calculated drying times for the cross-flow batch dryer (shown in Table 13) are plotted in Figure 25. The regression analysis is presented in Table 17. The correlation coefficients (r^2) for the in-bin counterflow dryer and for the cross-flow batch dryer were .990 and .997, respectively. Also, the variations from the regression lines, as measured by the standard error of estimates (Tables 16 and 17), were

Table 16: Regression analysis between the observed and calculated drying times for the in-bin counterflow dryer.

Source	Sum of Squares	df	Mean Squares
Regression	15906.28	1	15906.28
Residual	317.80	29	10.95
Total	16224.08	30	

F = 1451.45

0 degree coefficient = 3.517
1 degree coefficient = .943

Coefficient of determination = .980
Coefficient of correlation = .990
Standard error of estimate = 3.310

Table 17: Regression analysis between the observed and calculated drying times for the batch dryer.

Source	Sum of Squares	df	Mean Squares
Regression	5217.56	1	5217.56
Residual	27.49	7	3.9
Total	5245.06	8	

F = 1328.31

0 degree coefficient = 1.939
1 degree coefficient = .895

Coefficient of determination = .990
Coefficient of correlation = .997
Standard error of estimate = 1.981

relatively low (3.31 and 1.91 min) for the in-bin counterflow and batch dryer, respectively. Therefore, for practical purposes, the agreement between the experimental and calculated drying times is considered sufficient for Hukill's (1954) deep-bed drying model to be used in the calculation of drying time for the in-bin counterflow and batch dryers. As a function of the estimated drying time, the other drying parameters such as energy cost, energy efficiency, and dryer capacity can now be calculated.

The energy from liquid propane consumption, drying efficiency, drying time, and dryer capacity as calculated by the drying model and as measured in the field test for the cross-flow batch dryer are shown in Table 13. As expected, the differences between the values for calculated and observed LP consumption, drying efficiency, and dryer capacity (Table 13) are acceptable. Those values are directly dependent on the observed and calculated drying times in Figure 24. From ave. 1 to ave. 7 (Table 13), the cooling time was not included in the calculation of dryer capacity. The corn was unloaded at high temperature directly into the in-bin dryeration bin or into the combination drying bins. The lower dryer capacities for ave. 8 and ave. 9 (control batches) are a result of the amount of water removed and inclusion of the cooling time.

Besides the estimated drying time (time between two consecutive cycles for the in-bin counterflow dryer), Tables 14 and 15 contain the energy efficiency, dryer capacity, and amount of water removed per hour, determined as a function of the calculated drying time. In comparing the calculated values (per-hour basis) in

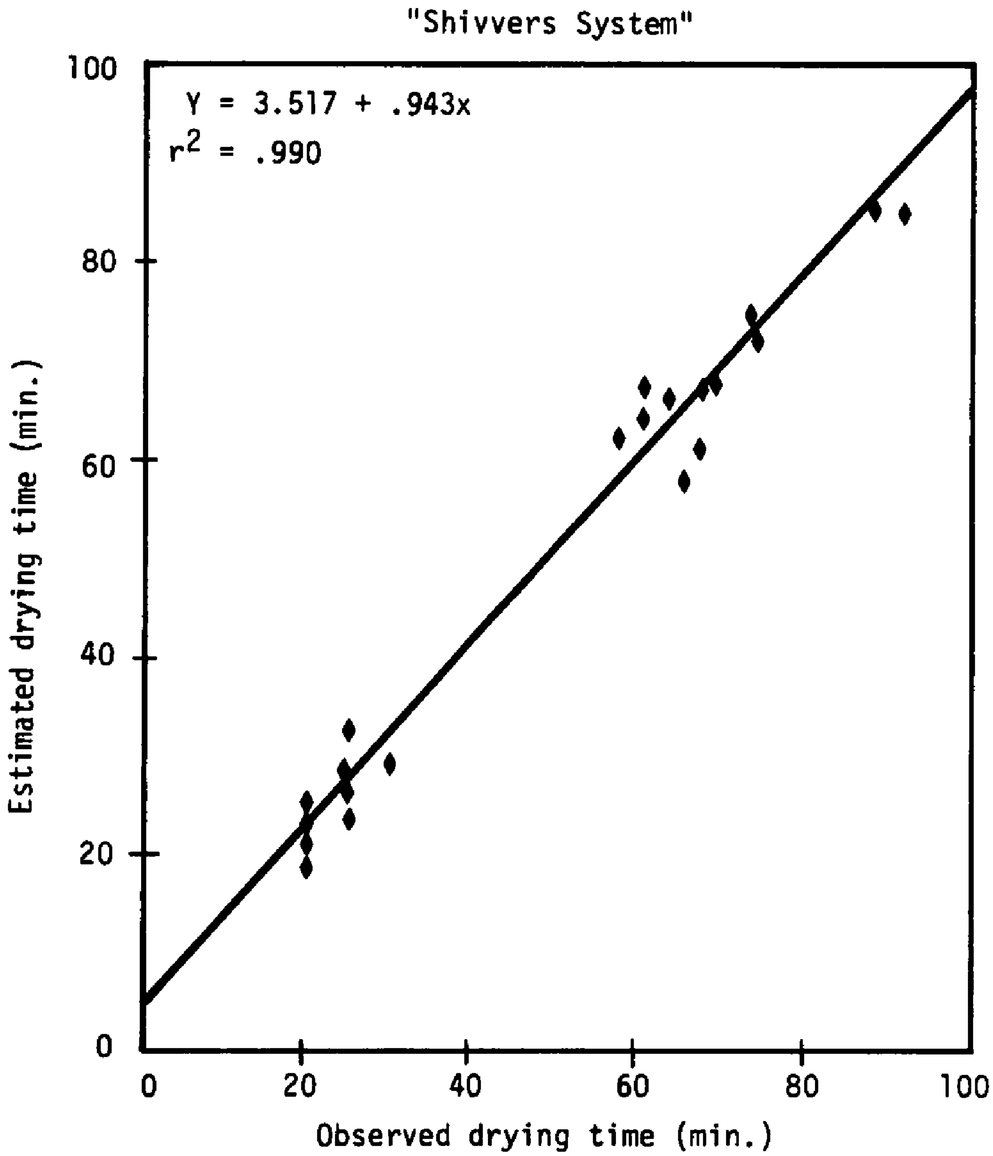


Figure 24. Relationship between the observed and estimated drying times for the in-bin counterflow dryer (cycling time).

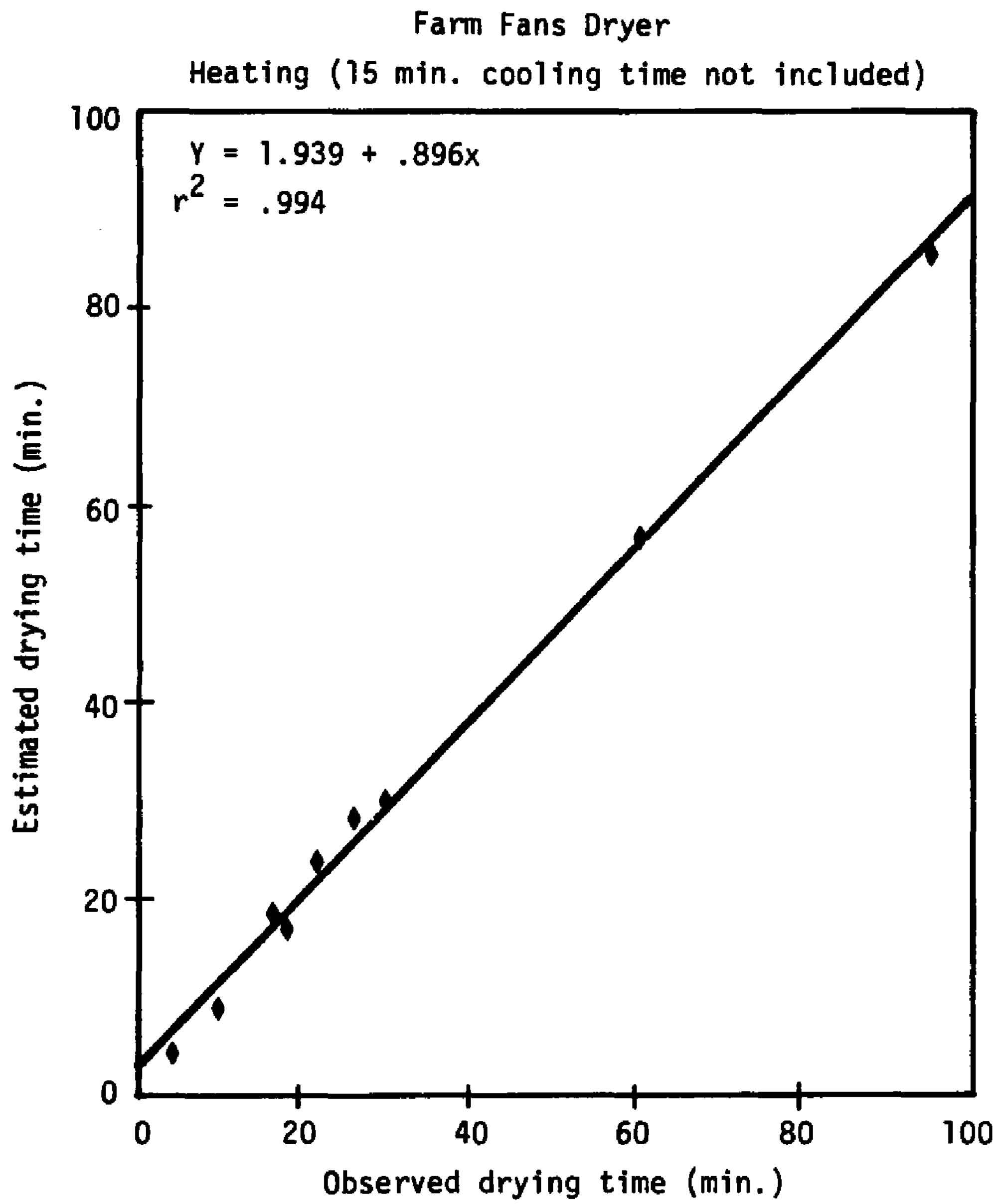


Figure 25. Relationship between the observed and estimated drying times using Equation 13 for the cross-flow batch dryer.

Tables 14 and 15 with the observed results in Tables 7 and 8, respectively, it should be kept in mind that the values in Tables 7 and 8 are based on cycling time. As for the batch dryer, the agreement between the calculated and observed results is acceptable. The propane equivalent values presented in Tables 14 and 15 refer to the total energy used (propane + electricity) put into a propane basis. The low dryer capacities shown in Table 15 are a result of the large amount of water removed for the 1979 tests.

5.5.2 Dryer Parameters Study

As previously stated, knowledge of energy efficiency, dryer capacity, operating costs, and management is needed if one is intelligently to select a drying system that will be suitable for its particular situation.

To have an ideal comparison between grain dryers, it is necessary that each dryer manufacturer or the governmental agency in charge of the grain drying and storage sector supply buyers with reports on dryer performance, completely field tested with different grains over a wide range of moisture contents and ambient conditions. However, exhaustive experimental testing of every model of dryer actually marketed in the United States would be exorbitantly expensive. Bakker-Arkema et al. (1978) suggested that simulation models can complement field experimentation and can make the process of rating dryers less time consuming and less costly. The system of equations used in the simulation programs is so complex that only digital computers with large memories can be used. Hukill's (1954) drying model, on which the dryer analyses that follow were based, can easily be implemented on small computers.

Among the factors affecting the performance of a grain dryer, initial and final moisture contents, airflow rates, ambient conditions, air temperature, and dryer design will be discussed. To facilitate the comparison, the two high-temperature drying systems will be considered simultaneously.

5.5.2.1 Drying temperature versus drying time and dryer capacity. In Figures 26 and 27, the drying time and dryer capacity are shown as a function of inlet air temperature and initial and final moisture content (25-18.5% and 25-15.5%) at constant ambient conditions for the "Shivvers" in-bin counterflow and the Farm Fans batch dryer, respectively. The drying conditions are 10°C, 70% relative humidity, 3.15 $m^3/min/m^2$ for the in-bin counterflow and 9.73 $m^3/min/m^2$ for the batch dryer.

As expected, Figures 26 and 27 show the same basic shape (increase in dryer capacity and decrease in drying time as temperature increases). The figures show that the drying-air conditions substantially alter dryer capacity, especially when drying at lower temperatures.

The decrease in drying time with an increase in dryer capacity is more pronounced for the batch dryer (Figure 27) because of its higher drying temperatures and higher airflow rate. However, drying at the recommended air temperature, the in-bin counterflow dryer presents a greater capacity (2.77 tons at 72°C--Figure 26) than the batch dryer (2.46 tons at 101°C--Figure 27) under consideration.

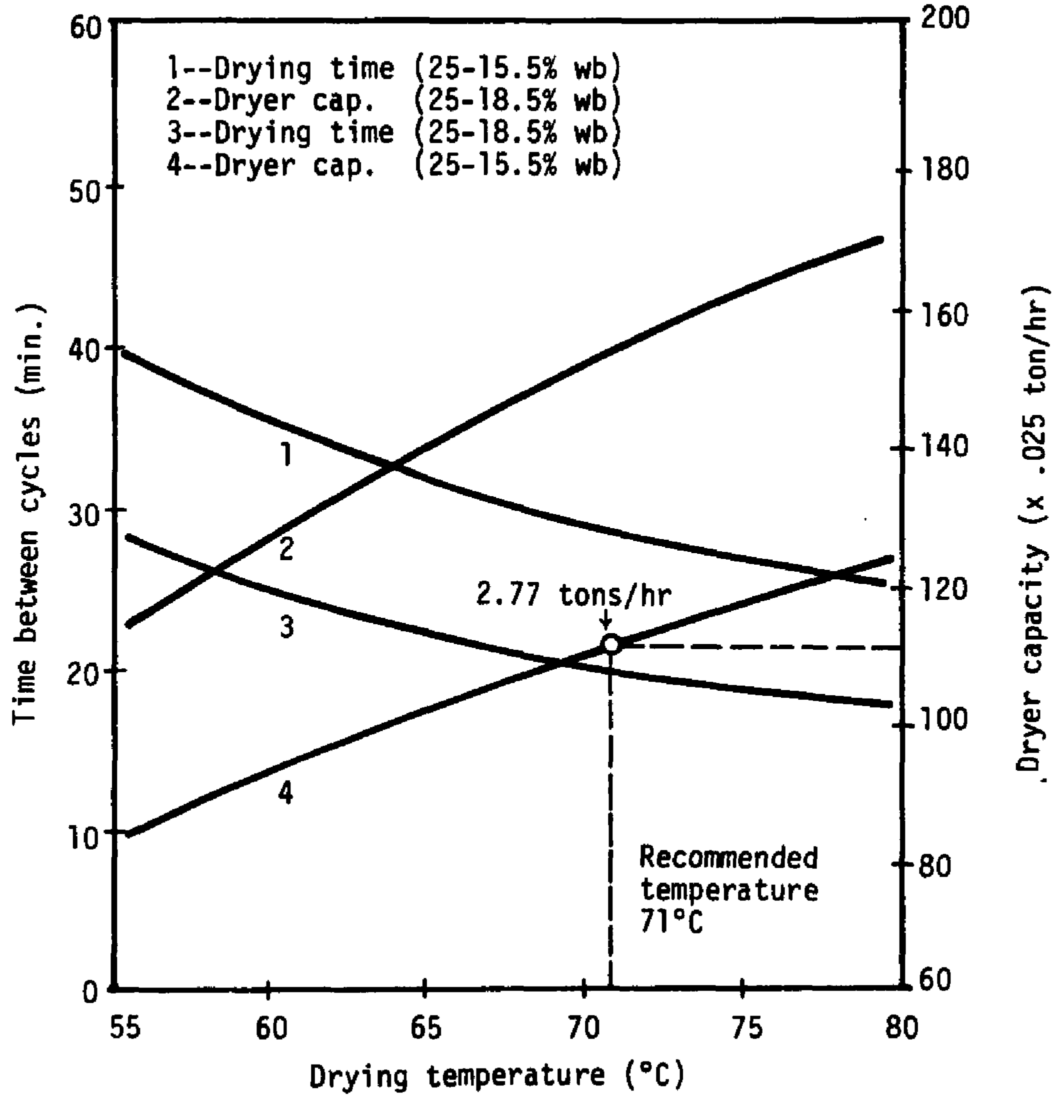


Figure 26. Effect of drying temperature and desired final moisture content on the drying time and dryer capacity for the "Shivvers" in-bin counterflow dryer at 34 cfm/ft^2 (9.4 cm H_2O).

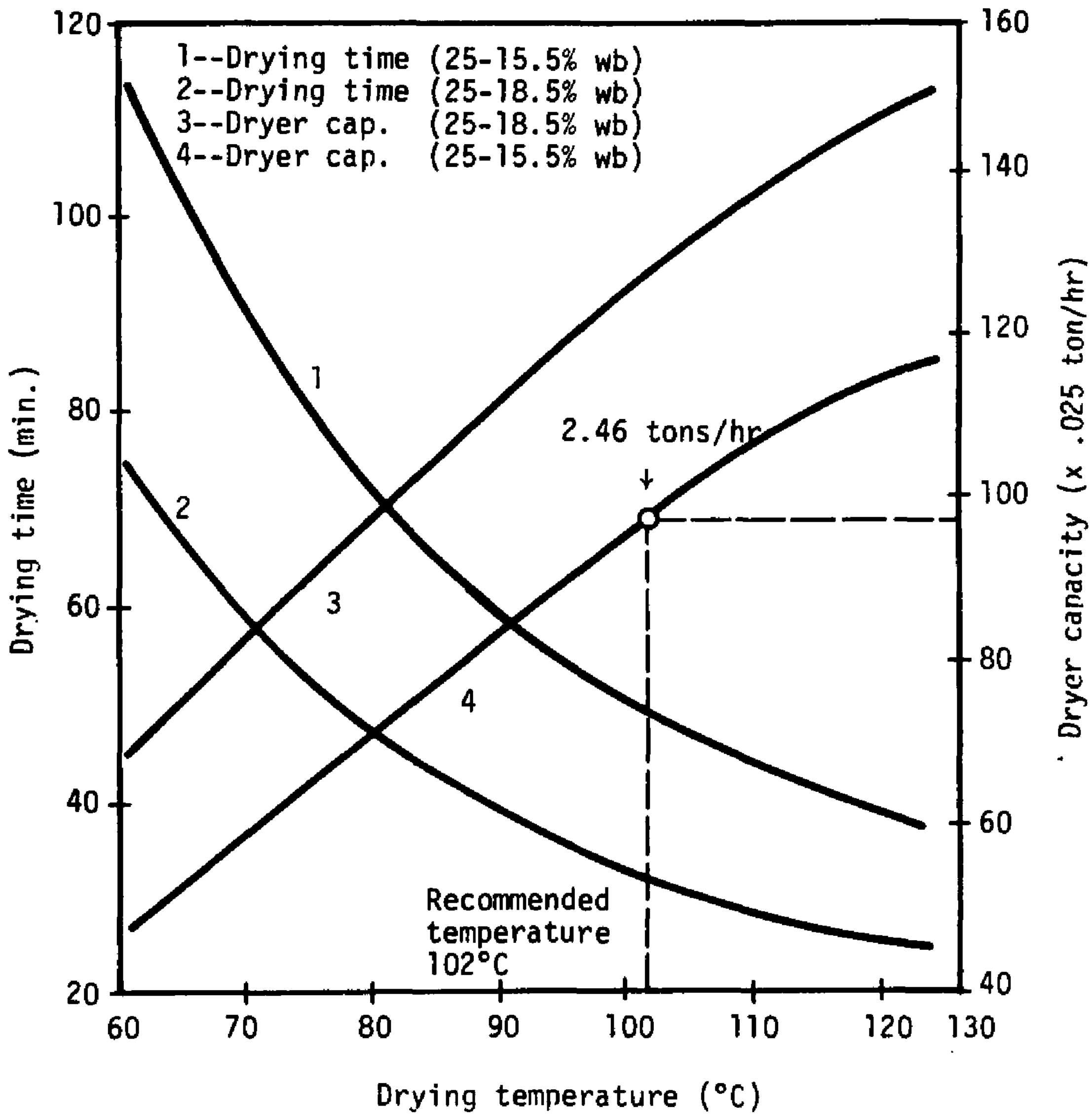


Figure 27. Effect of drying temperature and desired final moisture content on the drying time and dryer capacity for the "Farm Fans" batch dryer.

The time required to warm up the grain as each batch is processed, loading time, and unloading time greatly affect the capacity of a batch dryer. Because of the continuous-flow characteristics of the "Shivvers" system and because air (hot and dry) exhausted from the bottom layers warms up and partially dries the subsequent layers, the capacity of the dryer is not affected by the aforementioned factors.

Because dryeration or in-bin cooling can be used in combination with batch drying, cooling time has not been included in the calculation of batch-dryer capacity shown in Figure 27. Including the cooling time, the batch-dryer capacity will be lower than that presented in Figure 27. The 2.46 tons/hr indicated in the figure will be decreased to 1.97 tons/hr if the approximate 15 min. cooling is considered.

5.5.2.2 Drying temperature versus drying efficiency and total energy cost. Figures 28 and 29 illustrate the effect of drying temperature on the total energy cost and drying efficiency of drying shelled corn from an initial moisture content of 25% to 15% and 18.5% wb for the "Shivvers" and Farm Fans systems, respectively. The airflow rates are 3.15 $m^3/min/m^2$ (Figure 28) and 9.73 $m^3/min/m^2$ (Figure 29) for the "Shivvers" in-bin counterflow and the Farm Fans batch dryer, respectively. The figures are for ambient conditions of 10°C and 70% relative humidity. Both figures present the same basic tendency (decrease in KJ/Kg of water with decrease in energy cost). For the in-bin counterflow dryer, the changes are less pronounced. This suggests that drying-air temperature has a strong

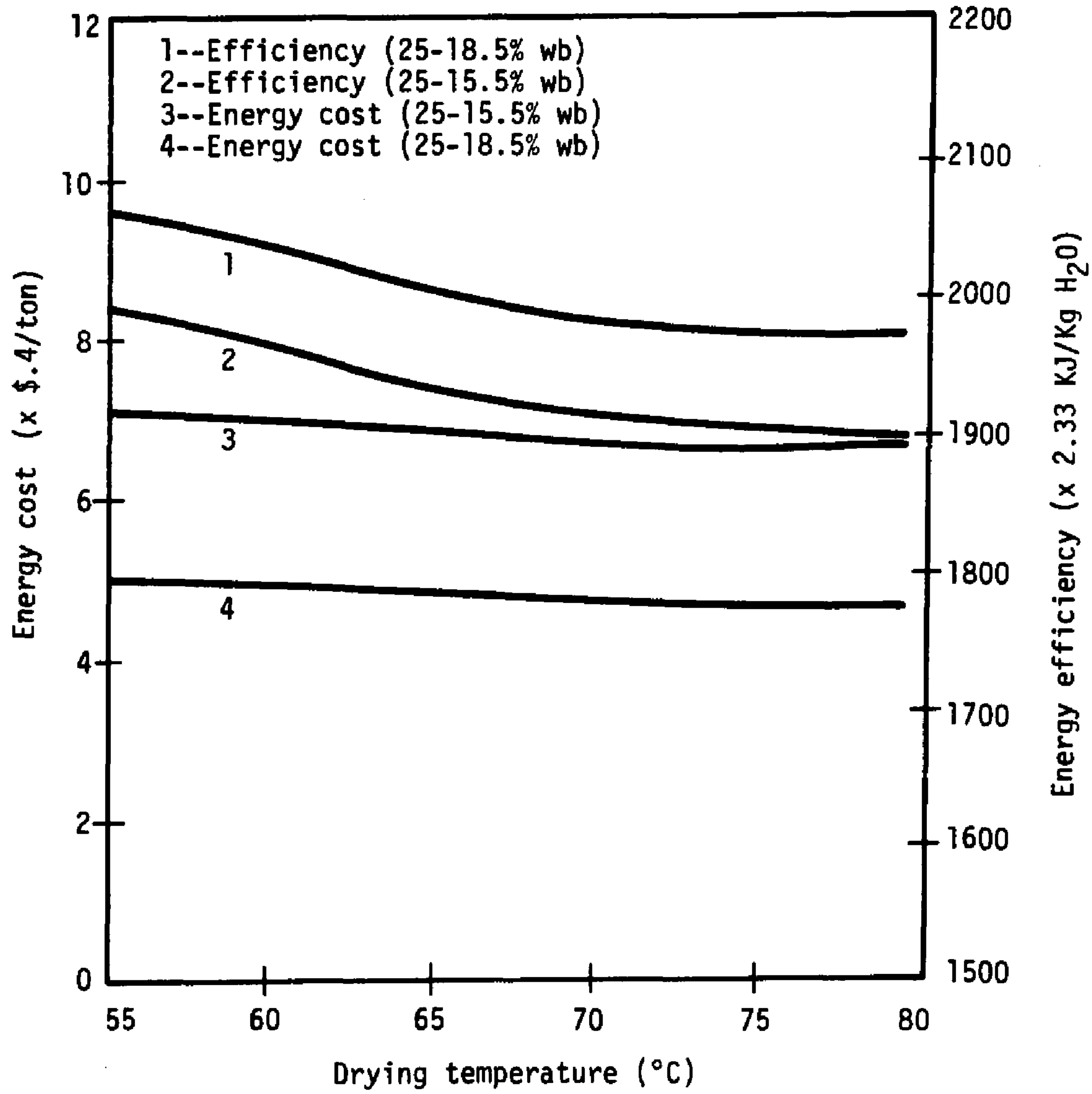


Figure 28. Effect of drying temperature and average final moisture content on the energy cost and drying efficiency for the "Shivvers" in-bin counterflow dryer under consideration.

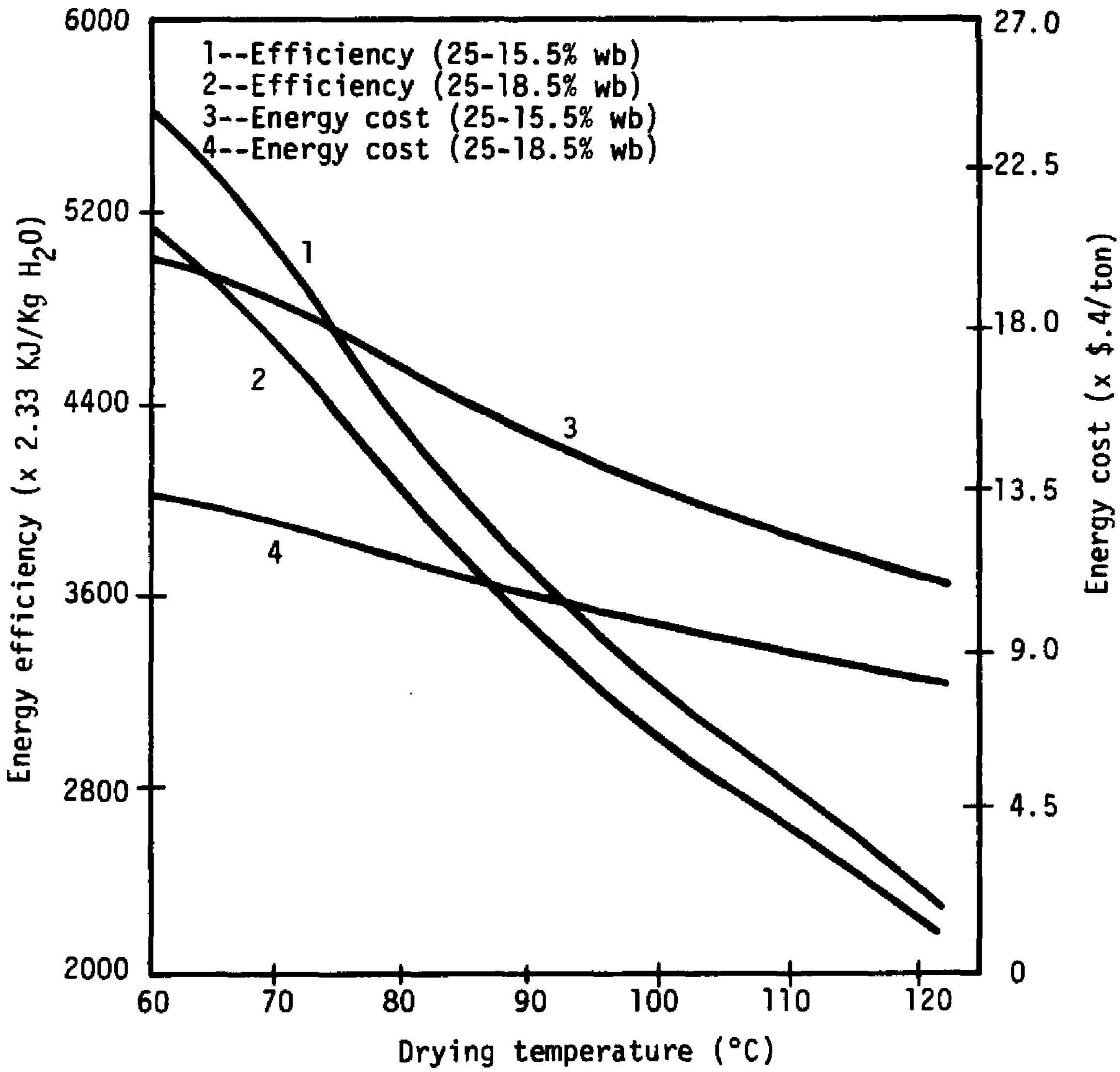


Figure 29. Effect of drying temperature and average final moisture content on the energy cost and drying efficiency for the "Farm Fans" batch dryer under consideration.

effect on the drying cost and energy efficiency of the batch dryer. Again, the exhaust air from the layer being dried in the in-bin counterflow system plays a major role in its good performance. As the warmer and less humid air leaves the bottom layer, it heats up the upper layers, resulting in more rapid water removal. Figure 28 suggests that drying at temperatures higher than presently recommended for the in-bin counterflow system (71°C) has no significant effect on the energy cost and efficiency of the system. This result reflects the assumptions of the in-bin counterflow simulation model. However, as shown in Figure 26, dryer capacity is highly affected by air temperature. In this case, product quality should be the deciding factor in selecting the ideal drying temperature for the in-bin counterflow dryer. Because of the almost linear increase in drying efficiency and decrease in energy cost for the cross-flow batch dryer (Figure 29), more difficulty is encountered in choosing the most efficient temperature. Product quality and moisture-content gradient across the grain column will limit the operating temperature.

5.5.2.3 Ambient relative humidity and drying temperature versus dryer efficiency. The effect of ambient relative humidity and drying-air temperature on the efficiency of the in-bin counterflow dryer is shown in Figure 30. The values are for 25.5% to 15.5% moisture content (wb), ambient temperature (10°C), and 3.15 $m^3/min/m^2$ of airflow. The figure shows that ambient relative humidity and drying-air temperature have opposite effects on dryer efficiency. The lower the drying temperature and the higher the ambient relative humidity, the less efficiently the system will perform. For the

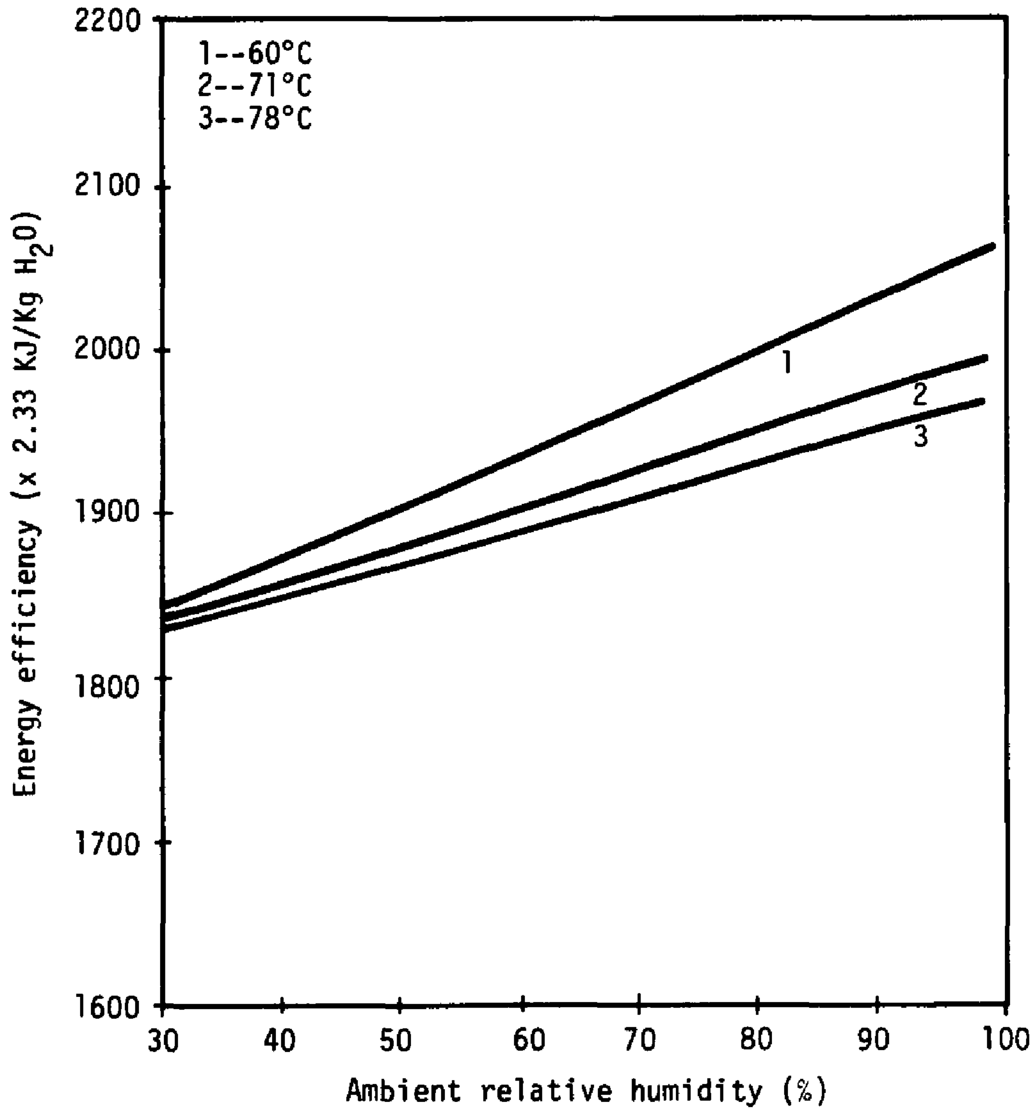


Figure 30. Effect of the ambient relative humidity and drying-air temperature on the drying efficiency of the in-bin counterflow dryer.

lower ambient relative humidity, the effect of drying temperature is less pronounced. Figure 30 shows that for the same ambient relative humidity, the effect of drying temperature is decreased as drying temperature increases. This condition suggests that for a specific relative humidity, there is a temperature limit above which no substantial reduction in dryer efficiency will take place. This is also shown in Figure 28, in which the energy-cost line tends to be parallel to the abscissa.

Because of the insignificant change (less than 2% from 20% to 100% relative humidity) in drying efficiency, a figure similar to Figure 28 is not presented for the cross-flow batch dryer.

5.5.2.4 Effect of moisture content on energy efficiency and drying time. The estimated heat energy and drying time required to dry corn from two initial moisture contents are shown in Figure 31 (in-bin counterflow dryer) and Figure 32 (cross-flow batch dryer). The operating conditions are 71°C, 3.15 $m^3/min/m^2$, and 102°C and 9.73 $m^3/min/m^2$ for the in-bin counterflow and batch dryer, respectively. For both figures, the ambient temperature is 10°C and the relative humidity 70%. As in Figure 26, the time shown for the in-bin counterflow drying is the cycling time, whereas for Figure 31 only the heating time is considered. Figures 31 and 32 clearly show that the drying time decreases as a smaller amount of water at low initial moisture content is removed. On the other hand, Figures 31 and 32 exhibit completely different behaviors with respect to heat-energy requirements.

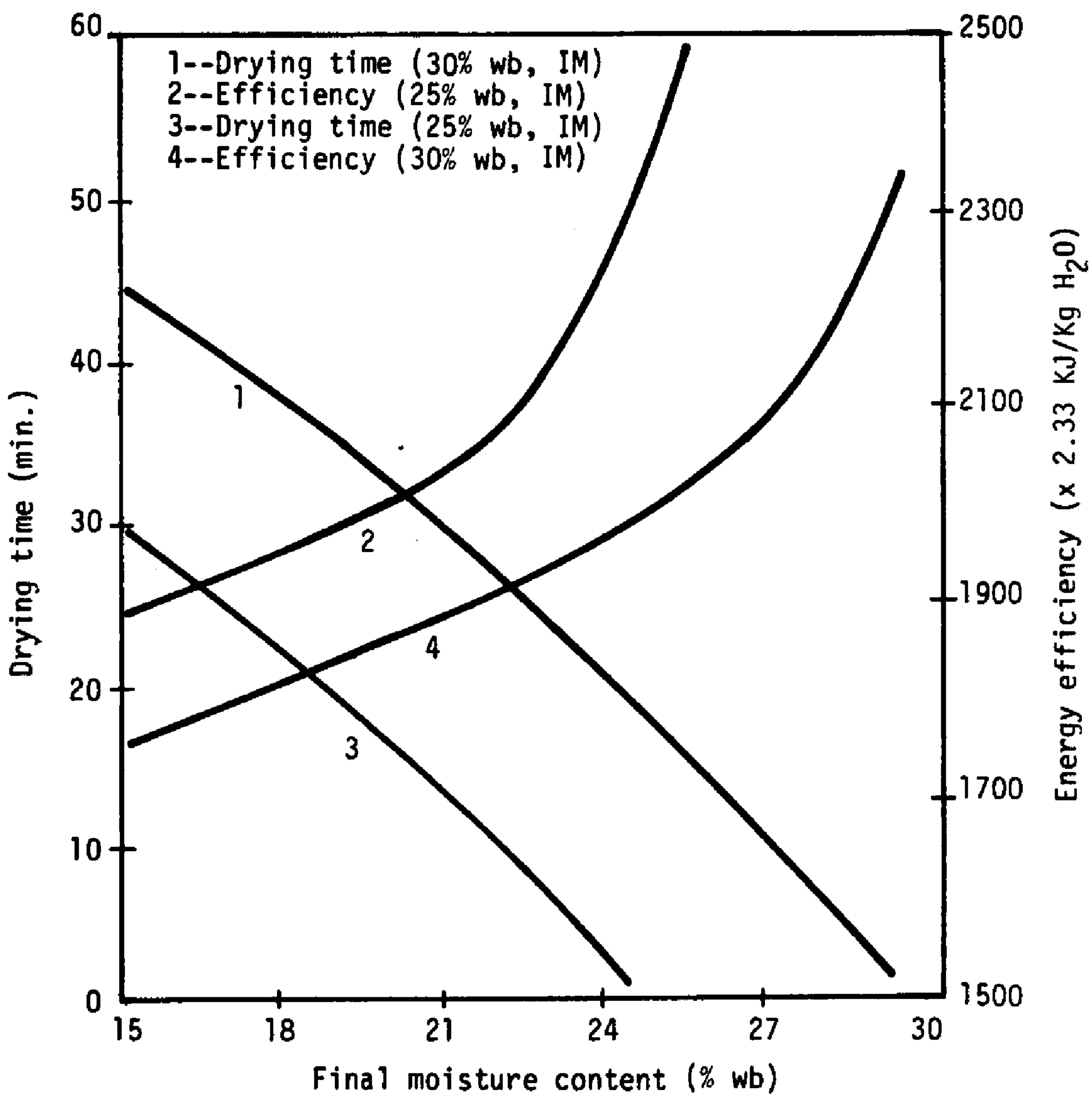


Figure 31. Effect of initial and final moisture content on the drying time and drying efficiency of the in-bin counterflow dryer under consideration.

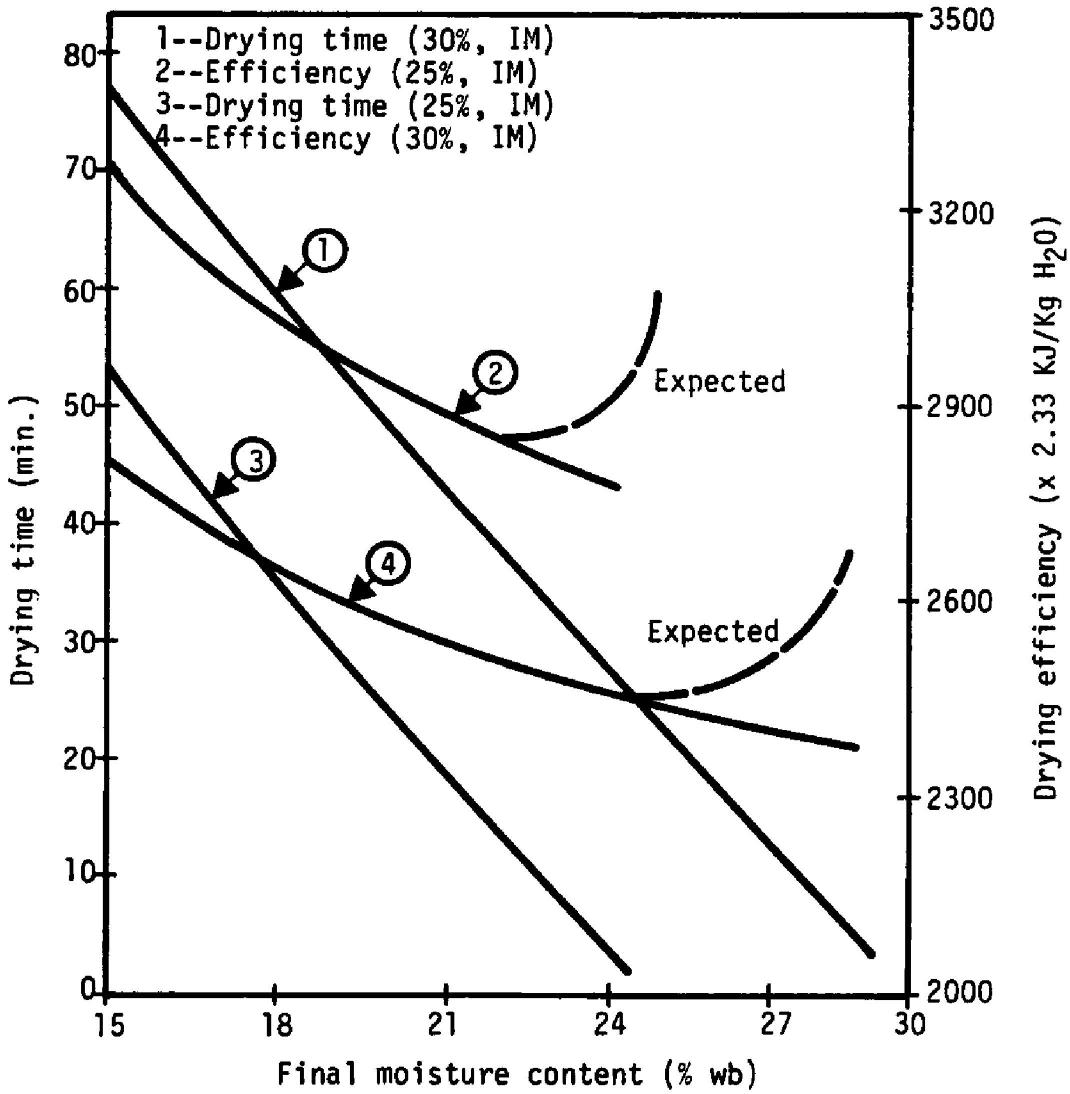


Figure 32. Effect of initial and final moisture content on the drying time and drying efficiency of the cross-flow batch dryer under consideration.

Despite having the normal characteristic of energy-efficiency curves for cross-flow dryers, Hukill's (1954) analysis fails to predict drying efficiency at the beginning of the process. The dotted lines shown in Figure 32 represent the expected behavior of a cross-flow dryer (Morey et al., 1976). Failure to predict drying efficiency for a small amount of water removed can be explained by the fact that Hukill's (1954) analysis does not account for the heat required to warm up the grain. For the normal drying range (above 3 points removal), the writer feels that the model can satisfactorily be used to predict efficiency for the cross-flow system.

Unlike other types of dryers, such as batch or cross-flow, the in-bin counterflow dryer requires less energy with a decrease in the final moisture content (Figure 31). However, a sufficient bed depth (over .9 m) must be maintained to guarantee a saturated exhaust-air condition. Since cooling does not occur in in-bin counterflow dryers, grain will carry enough sensible heat to remove 1 to 1.5 points of moisture, which will result in additional energy savings since drying can be completed with natural air.

In Brazil, corn is harvested from April to August, when the average ambient temperature is about 20°C and relative humidity 70%. The corn moisture content during the harvesting season varies from 16 to 22% wb. Because of Brazil's tropical condition, 13% wb or less is required for safe storage. Results of simulation indicate that to dry corn from 18 to 13% wb under Brazilian conditions, 3988 and 8243 KJ/Kg H_2O are required for drying with in-bin counterflow and cross-flow batch dryers, respectively.

5.5.2.5 Airflow rate versus drying cost and dryer capacity. The effect of airflow rate on drying cost and dryer capacity for the in-bin counterflow and batch dryer is shown in Figures 33 and 34, respectively. Again, if sufficient bed depth is maintained, the behavior of the energy-cost line for the in-bin counterflow dryer will be different than that for the batch dryer. Along with the benefit of decreased operating costs, the in-bin counterflow dryer shows a large increase in capacity when compared to the batch dryer at the same increment in airflow. Figure 33 shows that the airflow has more effect on dryer capacity than on the energy cost, whereas in the case of the batch dryer (Figure 34), both energy cost and dryer capacity are equally affected by the airflow rate.

5.6 Economics of the Systems

5.6.1 General Considerations

In analyzing the cost data presented in Tables 11 and 12 or predicted by the drying model (Figures 28, 29, 33, and 34), it should be kept in mind that only the direct electricity and fuel costs (operating costs) were considered. It would not have been realistic to include the labor and fixed costs since none of the systems analyzed at the Kalchik Farms are built at optimum size. The main objective of this study was not to find the total annual cost of each drying technique, but rather to demonstrate the feasibility of natural-air and low-temperature combination drying, in-bin dryeration, and in-bin counterflow drying for the Michigan weather conditions.

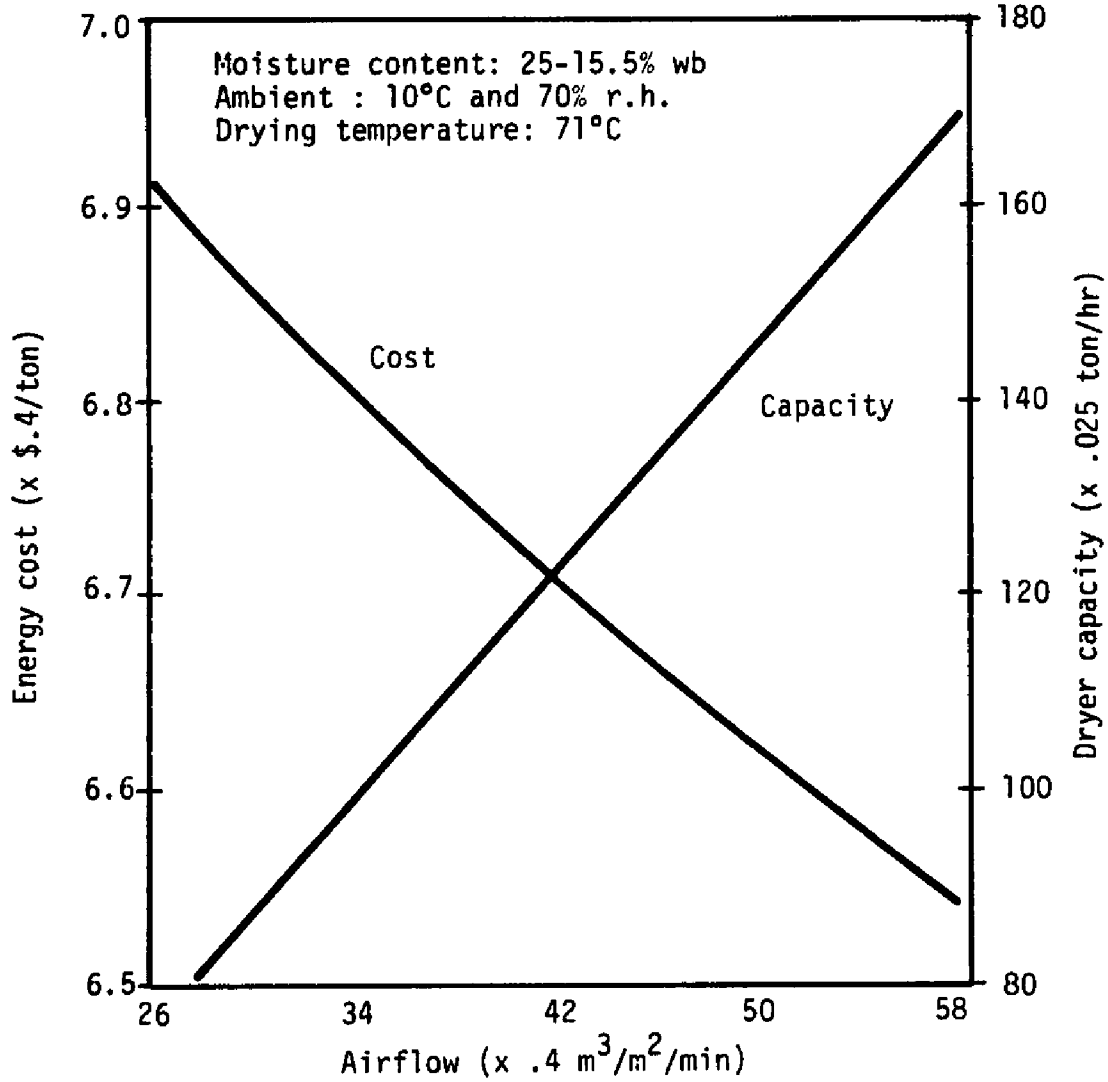


Figure 33. Effect of airflow rate on dryer capacity and energy cost for the "Shivvers" in-bin counterflow dryer.

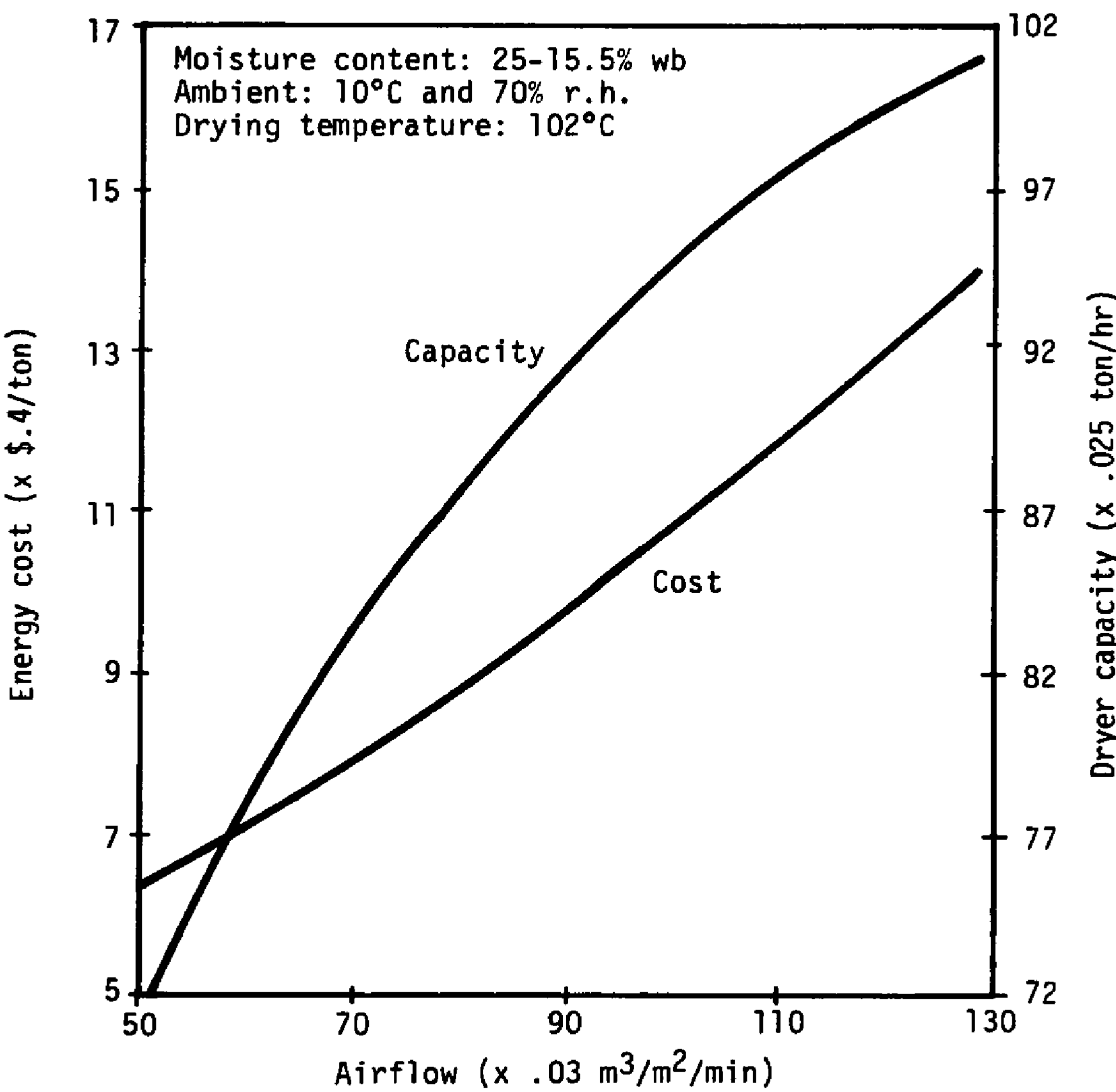


Figure 34. Effect of airflow rate on dryer capacity and energy cost for the "Farm Fans" batch dryer under consideration.

Although some farmers buy an on-farm drying and storage system solely because the dealer has convinced them to do so, most farmers consider on-farm grain drying only if it is likely to be cost competitive with other alternatives. To help farmers or farm managers make sound comparisons between the techniques studied, a 378-ton drying and storage capacity was designed for each technique. The following sections contain the economic comparison of the various techniques studied.

5.6.2 Capital Budgeting Analysis

Much more is involved with adoption of one of the systems than fuel, electricity, and labor costs. As with any kind of business enterprise, farmers use systems that are most profitable in the long run for their particular circumstances.

The economic choice among the five drying systems studied can be based entirely on current operating costs or elevator charges only if it is assumed that the various choices will all increase in price at the same rate. In this case, an on-farm grain-drying and storage system will be competitive or less expensive than off-farm drying and storage if the savings are greater than the interest payments required to buy the on-farm grain-drying system. A serious problem with this single comparison in an inflationary economy is that it is difficult to take into account rising electricity, fuel, and labor costs, as well as elevator charges. Also, other items such as taxes, insurance, maintenance, and labor costs affecting the economics of an on-farm grain-drying system have to be taken into consideration.

According to Skees et al. (1979), capital budgeting accounts for the net present value of alternative investments, allowing for cost comparison of investments with different annual flow of expenses and/or income. Factors such as interest rate and life of the loan, depreciation life and schedule chosen, marginal tax rate, eligibility for investment tax credit, and effects of inflation on variable cost are taken into account in the net present value capital budgeting approach.

The net present value method provides a means of comparing future costs with current costs by reducing all costs to the common basis of present worth, that is, the amount that one would have to invest today in order to have enough funds available in the future to meet all of the anticipated expenses.

Although net present value capital budgeting is considered as a sound approach for evaluating investment decisions (Skees et al., 1979), it has one major problem: the decision maker must be able to predict future costs. Future costs such as for fuel, electricity, labor, custom operation charges, and the rate of inflation must be accurately estimated.

5.6.3 Budgeting Analysis of the Systems

In order to have a sound comparison among the drying systems, a capital-budgeting analysis for the five alternative drying systems was performed. The estimated cost per ton includes both ownership costs and operating costs. It is calculated on a present-value basis.

Each of the 378-ton systems was designed to meet the Kalchik Farms' corn production for a 16-day drying season at 10 hours per day. The 16-day season allows some extra drying days for the combination-drying systems and will permit some custom drying. If custom drying is considered, it will generate extra income and greatly reduce the total annual per-ton cost. However, the possibility of custom drying was not taken into account in this analysis.

Although storage bins larger than the size designed (177 tons) are less costly (per-ton storage basis), the smaller bins permit more flexibility for the conditions on the Kalchik Farms. Appendix A specifies the components of each system and their estimated 1980 investment cost (the costs presented may vary among dealers). To arrive at the present-value annual per-ton cost of the systems, a computer program (TELPLAN 03) that estimates costs under different assumptions with respect to economic factors such as interest rates, tax rates, inflation, and other costs was employed. The reader is directed to Appendices B and C and for further information to the work done by Skees et al. (1979), who performed a detailed cost analysis for different drying systems for multiple use.

5.6.3.1 Costs and basic assumptions. One of the most important factors affecting variable costs is the energy requirement. The energy-cost values used in this analysis were calculated based on the drying model and experimental determinations (electricity to run the fans during the second drying phase) in Table 12. For the high-temperature phase, the ambient condition was 10°C and 70% relative humidity, with drying-air temperatures of 71 and 102°C for the in-bin counterflow and batch dryer, respectively. The energy costs for the different techniques are shown in Table 18. Assumptions concerning repair, labor requirements, and salvage value varied among the different systems and were chosen according to the values in Appendix A and in Table 18.

A number of other assumptions were made for the different systems: (a) a 10-year planning horizon, (b) purchase during August of the first year, (c) eligibility for the 10% investment tax credit, (d) use of double-declining balance depreciation with additional first-year depreciation (20%), (e) a \$.39/ton fuel cost for operating associated equipment, (f) a 30% marginal tax rate for the producer, (g) a 10% annual compounded increase in fuel cost, (h) an annual insurance charge of 1% of the inventory value of investment, (i) an annual insurance charge of 1% of the inventory value of investment, (j) an annual property tax of 1.6% of the inventory value of investment, and (k) a 6% annual compounded increase in investment costs of a new on-farm grain-drying and storage system. A loan rate of 7.8%, to be repaid over eight years, was assumed. The discount rate, which is considered a tool to cover risk of the investment, the time value of money, and opportunity to invest in a more profitable enterprise, must be assumed above the rate on borrowed money (7.8%). In this analysis, an after-tax rate of 9% was assumed.

The results of the economic analysis of the five on-farm drying systems (378-ton capacity) are shown in Table 19. The values associated with each design are for total, fixed, and variable costs and are presented in terms of the annual present value. The annual

Table 18: Estimation/assumptions for investment cost, salvage value, interest, direct and indirect energy costs, labor, and maintenance costs for the five drying systems.

Estimation/Assumption	Drying Systems				
	Batch Drying 2.41 ton/hr.	In-Bin Counterflow 3.81 ton/hr.	Batch--Low-Temp. Comb. Drying 5.8 ton/hr.	Batch--Nat.-Air Comb. Drying 5.8 ton/hr.	In-Bin Dryeration Drying 4.3 ton/hr.
Investment cost (1980 prices) (%)[a]	35,126.00	41,538.00	38,286.00	38,274.00	36,332.00
% Salvage value of total investment (%)	15%	14%	14%	15%	15%
Annual rate of interest on loan (%)	7.8%	7.8%	7.8%	7.8%	7.8%
Direct energy cost ($/ton)[a]	4.53	2.72	5.31	4.09	2.76
Indirect energy cost ($/ton)	.39	.39	.39	.39	.39
Labor cost ($/ton)	1.80	1.16	.89	.89	1.06
Maintenance cost (10 years)($)	1,756.00	2,076.00	1,914.00	1,948.00	1,816.00

[a]Based on $.62/kwh and $.127 per liter of propane.

Table 19: Economic analysis of five alternative on-farm corn-drying and storage systems for Michigan weather conditions (1980 prices).

System (378 tons annually)	Annual Cost Per Ton[a]			Initial Capital Investment Per Ton
	Fixed Cost	Variable Cost	Total Cost	
Batch drying (26.0-15.5% wb)	$7.23	$8.59	$15.82	$ 92.93
In-bin counterflow (26.0-18.0-15.5% wb)	8.51	5.83	14.34	109.89
In-bin dryeration (26.0-20.0-15.5% wb)	7.31	5.71	13.02	96.12
Natural air (26.0-23.0-15.5% wb)	7.85	7.24	15.09	101.25
Low temperature (26.0-23.0-15.5% wb)	7.84	8.78	16.62	101.29

[a]Net present value for a 10-year planning horizon.

nondiscounted returns, selected cost, and cash flow for each system are presented in Tables 20, 21, 22, 23, and 24 (Appendix A) for the batch, in-bin counterflow, in-bin dryeration, natural-air, and low-temperature combination drying systems, respectively. (See TELPLAN 03 User's Guide in Appendix C for a better understanding of the tables.)

Since the fixed costs were not substantially different for the five drying system designs, the total drying costs were more affected by the variable costs, as shown in Table 19. The least expensive system per ton is the in-bin dryeration. The in-bin counterflow ranks second. Although the low-temperature combination drying system has a fixed cost lower than the natural-air system, the high total cost for the low-temperature system can be explained by its strong dependence on electrical energy to run the fan and to heat the air. A similar comparison can be made for the natural-air combination drying and in-bin counterflow drying systems. Although the natural-air dryer is a less expensive investment and more energy efficient than the in-bin counterflow system (Table 12), the natural-air system requires too much electricity to run the fans during the drying and storage phases. Without question, the less expensive system in terms of initial investment per ton is batch drying. However, it ranks last among the systems studied because of the unfavorable price projection for fossil fuel in the near future. The energy and money savings ($1028 less than batch drying for a 378-ton annual capacity) more than offset the additional time and extra care required for the in-bin dryeration system. Natural air holds the most promise in terms of future fuel cost. However, it is a risky operation, and further research must be done with regard to the Michigan weather conditions.

To conclude this section, it should be kept in mind that any decision to invest in a new grain-drying system should take into account commercial drying and storage prices, adequacy of local marketing, and grain elevators. No doubt, more realistic assumptions can be made for each particular case. It may well be that the best alternative for some farmers would be to provide total drying and only partial or no storage facilities for their crop.

TELPLAN 03, which uses the net present-value capital budgeting, is "on line" and is available for routine use by extension, research, education, and agribusiness people to conduct economic analyses without the need of any programming knowledge (Brook & Bakker-Arkema, 1978).

6. SUMMARY

1. Except for the high-temperature drying systems, the results obtained in this research for Michigan are slightly different than those reported for other parts of the United States, such as Kansas, Minnesota, and Nebraska. The Michigan conditions required higher airflow and/or lower initial moisture content than in the aforementioned states.

2. The quality of the end-product was affected by the drying procedure. The in-bin counterflow dryer produced dried corn with less susceptibility to damage than that produced by the cross-flow batch dryer.

3. When low-temperature, natural-air, and in-bin dryeration were used in combination, the number of kernels with stress-cracks and the breakage test results were substantially improved compared to both in-bin counterflow and batch drying.

4. The final moisture contents, 18.5 and 14.7% for the batch and in-bin counterflow dryers, respectively, were the most probable cause of the smaller difference in the reported breakage susceptibility for the 1979-1980 tests.

5. In any case in which the batch dryer was part of the drying system, the changes in viability were substantially higher than for the in-bin counterflow dryer. The high-temperature air used for the batch dryer accounts for the differences.

6. On the basis of operating cost (in drying to the same moisture contents), the in-bin counterflow dryer is preferable to a cross-flow batch dryer. However, on the basis of initial investment, the cross-flow batch dryer has a significantly lower initial cost than any other system.

7. The high drying efficiency of the low-temperature and natural-air combination drying systems did not reduce the total drying cost. The variable costs were highly affected by the price of electricity.

8. In times of uncertain or inadequate fossil fuel supplies, the combination drying systems are the best choice for drying corn on small and medium-sized Michigan farms.

9. The results of energy requirements, operating costs, fixed costs and their potential savings data for drying corn in Michigan suggest that in-bin dryeration and in-bin counterflow drying hold the most promise.

10. Considering that at least 60% of the Michigan corn crop is artificially dried, the annual energy savings for Michigan are on the order of 2.11×10^9 MJ. The dollar savings in operating costs are between $3 and $10 million (except for the low-temperature combination drying technique).

11. Hukill's (1954) analysis for deep-bed drying described drying time as a function of initial moisture content, final moisture content, position in the grain bed, and ambient and drying conditions with reasonable accuracy for both batch and in-bin counterflow drying systems.

12. Results of simulation indicate that for the Brazilian conditions (70% relative humidity and 20°C ambient temperature), the energy efficiencies for the in-bin counterflow and cross-flow batch dryer are, respectively, 3988 and 8243 KJ/Kg of water removed. This suggests that in-bin counterflow drying is also the best choice for the average Brazilian conditions.

7. SUGGESTIONS FOR FUTURE RESEARCH

Based on the findings of this study, the following suggestions are made for future research:

1. Conduct experiments to validate Hukill's analysis for the in-bin counterflow dryer over a wider range of drying temperatures and final moisture contents.

2. Apply other drying models to analyze the in-bin counterflow drying system.

3. Perform the tests in different locations and in different years in the state of Michigan.

4. Perform the low-temperature and natural-air combination drying using the in-bin counterflow or other more efficient dryers in the high-temperature phase.

5. Insulate the in-bin counterflow dryer and eliminate its potential heat leakage.

6. Test the in-bin counterflow dryer for drying temperatures above 72°C.

7. Study the performance of the bees-wing eliminator of the "Shivvers" system.

8. The effect of the uniformity of the grain-bed level should be investigated based on the final moisture-content variation of the in-bin counterflow dryer.

9. The adaptation of alternative burners such as for wood chips or corn cobs should be investigated in the "Shivvers" in-bin counterflow system.

10. The causes for the high variability in final moisture content for the cross-flow batch dryer should be investigated and changes in the design suggested.

11. The potential problems for in-bin dryeration and the two combination drying techniques increase as bin size increases. Therefore, the optimum bin size for each technique in relation to farm production and management should be investigated.

12. For the Brazilian conditions, corn is harvested between 16 and 22% initial moisture content; 13% final moisture is required for safe storage. Tests in this moisture range with the in-bin counterflow drying system should be conducted.

REFERENCES

REFERENCES

Anon. 1975. 1975 Corn Annual. Corn Refiners Association, Inc.

Atwai, A. S. 1974. Ecology of pest complex in stored grain. In Post-harvest Prevention of Waste and Loss of Food Grain. Asian Productivity Organization, Tokyo. 357 pp.

Bakker-Arkema, F. W., Bickert, W. C., and Patterson, R. J. 1967. Simultaneous heat and mass transfer during the cooling of deep bed of biological products under varying inlet air conditions. Journal Agric. Eng. Res. 12:297.

Bakker-Arkema et al. 1974. Energy in Michigan Agriculture. Agricultural Engineering Department, Michigan State University, East Lansing, Michigan.

Bakker-Arkema, F. W., Brook, R. C., and Brooker, D. B. 1978. Energy and capacity performance evaluation of grain dryers. ASAE Paper No. 78-3523.

Bakker-Arkema, F. W., Brook, R. C., and Lerew, L. E. 1978. Cereal grain drying. In Advances in Cereal Science and Technology, Vol. II, ed. by Y. Pomeranz. American Assoc. of Cereal Chem., Inc., St. Paul, Minnesota.

Bakker-Arkema, F. W., Hsieh, R. C., and Silva, J. S. 1979. Alternative method of on-farm grain drying in Michigan. M.S.U. Agric. Eng. Dept., unpublished report.

Bartsch, J. A., and Finner, M. F. 1976. A low-temperature grain drying experiment in an artificially reproduced environment. Trans. ASAE 19:373.

Batror, A. L. 1974. Rodents and Their Control. In Post-harvest Prevention of Waste and Loss of Food Grain. Asian Productivity Organization, Tokyo. 357 pp.

Boyce, D. S. 1965. Grain moisture and temperature changes with position and time during thorough drying. J. Agr. Engr. Res. 10(4):333.

Brasil. 1978. Instituto Brasileiro de Geografia e Estatistica, IBGE, Rio de Janeiro, Brasil.

Bridges, T. C., Ross, I. J., White, G. M., and Loewer, O. J. 1979. Determination of the optimum drying depth for batch-in-bin corn drying systems. ASAE Paper No. 79-3520.

Brook, R. C. 1971. Design of multistage grain dryers. Ph.D. dissertation, Michigan State University, East Lansing, Michigan.

Brook, R. C., and Bakker-Arkema, F. W. 1978. TELPLAN: A communication network to solve agricultural problems. ASAE Paper No. 78-5003.

Brooker, D. B., Bakker-Arkema, F. W., and Hall, C. W. 1974. Drying Cereal Grains. AVI Publication Co., Minneapolis, Minnesota.

Brooker, D. B., McKenzie, B. A., and Johnson, H. K. 1978. The present status of on-farm grain drying. ASAE Paper No. 78-3007.

Buelow, F., and Boyd, J. 1957. Heating air by solar energy. Agricultural Engineering 38(1):28.

CAST. 1977. Energy use in agriculture: Now and for the future. Agricultural Science and Technology, Report No. 68.

Chang, D. I., Chung, D. S., and Hodges, T. O. 1979. Grain dryer selection model. ASAE Paper No. 79-3519.

Chowdhury, M. R., and Kline, G. L. 1978. Stress cracks in corn kernels from compression loading. Paper No. 78-3541. ASAE, St. Joseph, Michigan.

Christensen, C. M., and Kaufmann, H. H. 1969. Grain Storage. University of Minnesota Press, Minneapolis, Minnesota. 153 pp.

Christensen, C. M., and Kaufmann, H. H. 1974. Microflora. In Storage of Cereal Grain and Their Products. American Association of Cereal Chemists, University Farm, St. Paul, Minnesota.

Copeland, L. O. 1976. Principles of Seed Science and Technology. Burgess Publishing Co., Minneapolis, Minnesota. 369 pp.

Cotton, T. R. 1953. Insects. In Storage of Cereal Grains and Their Products. American Association of Cereal Chemists, St. Paul, Minnesota. 515 pp.

Cotton, T. R. 1963. Pests of Stored Grain and Grain Products. Burgess Publishing Co., Minneapolis, Minnesota. 338 pp.

Dalpasquale, V. A. 1979. Continuous-flow drying of soybeans. M.S. thesis, Michigan State University, East Lansing, Michigan.

Dykstra, W. W. 1973. Rodents in stored grain. In Grain Storage: Part of a System. The Avi Publishing Co., Inc., Westport, Connecticut. 481 pp.

Evans, T. W. 1970. Simulation of counterflow drying. M.S. thesis, Michigan State University, East Lansing, Michigan.

Fedewa, D. J., Pscodna, S. J., and Molenda, E., Jr. 1978. Michigan Corn Harvesting and Marketing Statistics, 1977. Mich. Crop. Rep. Serv., Lansing, Michigan.

Feistritzer, W. P. 1975. Cereal Seed Technology. Food and Agriculture Organization of the United Nations (FAO), Rome. 238 pp.

Foster, G. H. 1964. Dryeration--A corn drying process. USDA Agricultural Marketing Service Bull. 532.

Freeman, J. E. 1978. Quality factors affecting value of corn for wet milling. In Proceedings 1977 Corn Quality Conference. University of Illinois, Urbana-Champaign, Illinois.

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

Hamdy, M. Y., and Barre, H. J. 1970. Analysis of hybrid simulation of deep-bed drying of grains. Transaction of the ASAE 13(6): 752.

Harris, K. L. 1973. Rodents in stored grain. In Grain Storage: Part of a System. The Avi Publishing Co., Inc., Westport, Connecticut. 481 pp.

Harsh, S. B., Rister, E., and Bakker-Arkema, F. W. 1978. Economic evaluation of on-farm grain drying and storage. Ag. Economics Staff Paper No. 78-100, Michigan State University, East Lansing, Michigan.

Hathaway, I. L., Yung, F. D., and Kresselbach, T. T. 1952. The effect of drying temperature on the nutritive value and commercial grade of corn. J. Animal Sci. 11:430.

Henderson, J. M., and Henderson, S. M. 1968. A computational procedure for deep-bed drying analyses. J. Agr. Engr. Res. 13(2): 87.

Hill, L. D. 1975. Test weight of corn as measure of quality. In Corn Quality in the World Markets, ed. by L. D. Hill. Interstate Printers and Publishers, Danville, Illinois.

Hukill, W. V. 1954. Drying of grain. In Storage of Cereal Grain and Their Products, ed. by J. A. Anderson and A. W. Alcock. American Association of Cereal Chemists, University Farm, St. Paul, Minnesota. 549 pp.

Hukill, W. V. 1974. Grain drying. In Storage of Cereal Grain and Their Products, ed. by J. A. Anderson and A. W. Alcock. American Association of Cereal Chemists, University Farm, St. Paul, Minnesota. 549 pp.

IBGE. 1978. Instituto Brasileiro de Geografia e Estatistica, Rio de Janeiro, Brasil.

Jensen, A. H. 1978. The effect of processing (roasting) on the nutritional value of corn for swine. In Proceedings 1977 Corn Quality Conference. University of Illinois, Urbana-Champaign, Illinois.

Jensen, A. H., Terrill, S. W., and Becker, D. E. 1960. Nutritive value of corn dried at 140, 180, and 220°F for swine of different ages. J. Animal Sci. 19:629.

Kalchik, S. J., Silva, J. S., and Bakker-Arkema, F. W. 1979. An engineering-economic comparison of five drying techniques for shelled corn on Michigan farms. Paper No. 79-3518. ASAE, St. Joseph, Michigan.

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

Kirk, D. E. 1959. Column thickness for shelled corn driers. Transaction of the ASAE 2(1):42.

Lipper, R. I., and Davis, C. P. 1960. Drying crops with solar energy. Agricultural Research 8(11):14.

MacMasters et al. 1959. A study of the effect of drying conditions on the suitability for starch production of corn artificially dried after shelling. Cereal Chem. 36:247.

McAdams, W. H. 1954. Heat Transmission. 3rd ed. McGraw-Hill Book Co., New York.

McKenzie, B. A., Foster, G. H., Noyes, R. T., and Thompson, R. A. 1972. Dryeration--better corn quality with high speed drying. Purdue University, Co-op Ext. Serv. Bull. AE-72.

McLendon, B. D., and Allison, J. M. 1978. Solar energy utilization in alternate grain drying systems in the Southeast. Paper No. 78-3013. ASAE, St. Joseph, Michigan.

Miller, B. S., Hughes, J. W., Rousser, R., and Pomeranz, Y. 1979. Standard method for measuring breakage susceptibility of shelled corn. Paper No. 79-8087. ASAE, St. Joseph, Michigan.

Morey, R. V., Cloud, H. A., and Lueschen, W. E. 1976. Practices for the efficient utilization of energy for drying corn. Transaction of the ASAE 19(14): 151.

Morey, R. V., Robert, J. G., and Cloud, A. H. 1978. Combination drying. In Proceedings of the Alternatives for Grain Conditioning and Storage Conference. University of Illinois, Urbana-Champaign, Illinois.

Paulsen, M. R., and Nave, W. R. 1978. Corn damage from conventional and rotary combines. Paper No. 78-7004. ASAE, St. Joseph, Michigan.

Peplinski, A. J. et al. 1975. Corn quality as influenced by harvest and drying conditions. Cereal Food World 19(2):145.

Peterson, W. 1973. Solar-electric crop dryer progress report. EMC 657. South Dakota State University.

Peterson, H. W., and Hellickson, M. A. 1976. Solar-electric drying of corn in South Dakota. Transaction of the ASAE 19(2):349.

Pfost, H. B., Maurer, S. G., Grosh, L. E., Chung, D. S., and Foster, G. H. 1977. Fan management systems for natural air dryers. Paper No. 77-3526. ASAE, St. Joseph, Michigan.

Pierce, R. D., and Thompson, L. T. 1978. Management of solar and low-temperature grain drying systems. Paper No. 78-3513. ASAE, St. Joseph, Michigan.

Pierce, R. D., and Thompson, L. T. 1978. Management of solar and low-temperature grain drying systems. Part I: Minimum airflow rates: Supplemental heat and fan operation strategies with full bin. Paper No. 78-3515. ASAE, St. Joseph, Michigan.

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

Rutledge, J. H. 1978. The value of corn quality to the dry miller. In Proceedings 1977 Corn Quality Conference. University of Illinois, Urbana-Champaign, Illinois.

Schmidt, S. C. 1978. Foreign market prospect for corn. In Proceedings 1977 Corn Quality Conference. University of Illinois, Urbana-Champaign, Illinois.

Shove, G. C. 1978. Corn quality as affected by drying procedures. In Proceedings 1977 Corn Quality Conference. University of Illinois, Urbana-Champaign, Illinois.

Shove, G. C. 1978. Corn drying with low temperature, high temperature combination system. Paper No. 78-305. ASAE, St. Joseph, Michigan.

Skees, J. R., Rister, M. E., Brook, R. C., Harsh, S. B., and Bakker-Arkema, F. W. 1979. On-farm grain handling costs--Engineering and economic factors. Paper No. 79-3525. ASAE, St. Joseph, Michigan.

Sobel, A. T., and Buelow, F. 1963. Galvinized steel roof construction for solar heating. Agricultural Engineering 44(6): 312.

Stevens, J. B., Barrett, J. R., and Okos, M. R. 1978. Mathematical simulation of low-temperature wheat drying. Paper No. 78-3004. ASAE, St. Joseph, Michigan.

Stewart, L. D. 1978. The significance of corn quality for feed manufacturer. In Proceedings 1977 Corn Quality Conference. University of Illinois, Urbana-Champaign, Illinois.

Stout, B. A. 1979. Energy for World Agriculture. FAO, United Nations, Rome, Italy.

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

Sutherland, J. W. 1975. Batch brain dryer design and performance prediction. Journal of Agric. Engr. Res. 20:423.

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

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

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

UREMG. 1968. Armazenamento nas Fazendas. Universidade Rural do Estado de Minas Gerais, Viçosa M.G., Brazil.

USDA. 1968. Preventing microtoxins in farm commodities. Agricultural Research Service, ARS 20-16.

USDA. 1975. Crop Production, 1975. Annual Summary. Statistical Reporting Service, USDA, Washington, D.C.

Veja. 1980. Corrida de obstaculo. Veja No. 601. Editora Abril, 12 de Março.

Veja. 1980. O campo conta os lucros da supersafra. Veja. No. 603. Editora Abril, 26 de Março.

Watson, S. A., and Mirata, Y. 1962. Some wet-milling properties of artificially dried corn. Cereal Chem. 39:35.

Williams, E. E., Fortes, M., Colliver, D. G., and Okos, M. R. 1978. Simulation of stirred bin low temperature corn drying. Paper No. 78-3012. ASAE, St. Joseph, Michigan.

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

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

Zink, H., Brook, R. C., and Peart, R. M. 1978. Engineering analysis of energy source for low temperature drying. Paper No. 78-3517. ASAE, St. Joseph, Michigan.

APPENDICES

APPENDIX A

BUDGETING ANALYSIS OF THE 378-TON (15,000 BU) DRYING SYSTEMS

A1. Batch Drying (15,000 bushels) (120 bu/hr)

1. System operation

From field → Moisture tester

↓

Grain cleaner

↓

Flight auger

↓

Wet holding tank

↓

17 ft. auger

↓

Batch dryer

↓

42 ft. auger → 5,000 bushels bin
42 ft. auger → 5,000 bushels bin
42 ft. auger → 5,000 bushels bin

Initial moisture content	26.0% (wb)
Final moisture content	15.5% (wb)

2. Estimated 1980 Investment Cost

Quantity	Item	Cost ($)
1	Batch dryer (120 bu/hr)	$ 8,170.00
3	24 ft. diameter bin (12 ft. ht.)	9,552.00
3	Perforated floor	4,665.00
3	Concrete	2,520.00
1	Wet holding tank (35 m^3)	2,235.00
1	Grain spreader	400.00
1	Grain cleaner	600.00
1	Unloading auger + motor	457.00
1	Sweep auger + motor	298.00
1	Flight auger + motor for loading the wet holding tank	3,500.00
1	42 ft. transport auger + motor (6")	2,050.00
1	17 ft. transport auger + motor (6")	750.00
3	Axial fan (5" SP 2500 cfm)	978.00
1	Moisture tester	220.00
	Electrical	1,000.00
	Total investment at list prices	37,175.00
	Less 10% discount	33,457.00
	Installation	1,000.00
	Miscellaneous (2% investment)	669.00
	TOTAL COST OF THE SYSTEM	$35,126.00

3. Estimated salvage value at the end of 10 years

According to Brook (1977), a dryer is made primarily of sheet metal, and although the metal may have some scrap value, the cost of disassembling it would make the total salvage value negligible; however, one half of bin, floor, installation, concrete, electrical, and miscellaneous cost remains at the end of 10 years.

For the total system:

Bins	$ 5,893.00
Perforated floor	2,332.00
Concrete	1,260.00
Electrical	500.00
Miscellaneous	334.00
Installations	500.00
Total	$10,819.00

at 50% salvage cost ($5,409.00).

% salvage of total investment = $5,409.00 ÷ $35,126.00 ≈ 15%.

4. Estimated annual rate of interest on loan

Harsh et al. (1978) assumed an annual rate of interest on loan equal to 7.8%.

5. Estimated direct energy cost

Experimental data at 1980 prices indicate $11.5/100 bushels.

6. The estimated indirect energy cost is assumed to be $1.00/100 bushels (Harsh et al., 1978).

7. Estimated labor cost

At 2.4 tons per hour drying capacity, 157 hours of labor ($4.00/hr) are required (loading and management). At 30 tons per hour unloading capacity, 13 hours are required. Total labor time = 157 hr + 13 hr = 170 hr. At $4.00/hr, labor cost will be equal to $680/378 tons or $1.80/ton.

8. Estimated maintenance cost over 10 years

Wood (1975) gave a range in the maintenance factor from 2 to 15% of the investment cost per year. A grain-drying system is made of relatively simple pieces of equipment. A maintenance cost of 5% of investment cost per year, including the bins, is assumed.

$35,126 x 5% = $1,756 (in 10 years)

To use TELPLAN 03, some basic assumptions must be made. For the batch drying and following designs, see respective TELPLAN forms and TELPLAN 03 User's Manual (Appendix C).

Table 20: General economic analysis for a 10-year period for the batch-drying system.

YR	TOTAL RETURNS	DEPREC-IATION	PRINC+ INT.	REPAIRS	FUEL+ LUB.	LABOR	SUP-PLIES	AFTER-TX CASH FLW
1	6266	6594	2528	127	2310	721	0	4842
2	6642	5706	5810	180	2495	764	0	-1634
3	7041	4565	5810	217	2694	810	0	-1862
4	7463	3652	5810	250	2910	859	0	-2048
5	7911	2922	5810	281	3142	911	0	-2200
6	8386	2337	5810	311	3394	965	0	-2328
7	8889	1870	5810	341	3665	1023	0	-2436
8	9422	1496	5810	371	3959	1084	0	-2531
9	9988	1197	3539	402	4275	1150	0	-268
10	10587	957	0	434	4617	1218	0	3249
TOTALS	82595	31296	46737	2914	33461	9505	0	-7216

1. ECONOMIC SAVINGS (DISCOUNTED DOLLARS) OVER PEROID OF USE IF INVESTMENT IS MADE = $ -10.

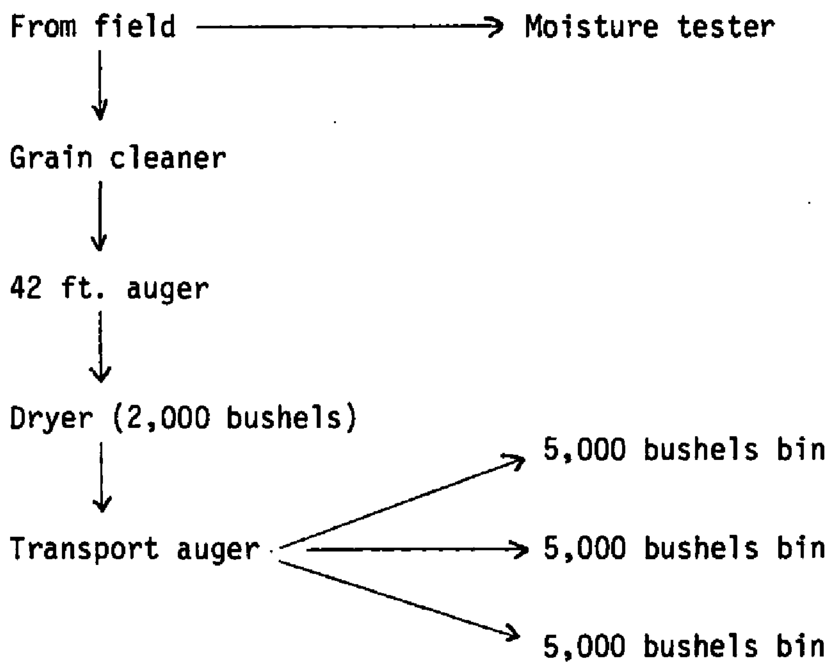
2. NUMBER OF UNITS ON WHICH ANALYSIS WAS MADE = 378.

3. DEPRECIATION METHOD USED IN ANALYSIS = 4.

4. ANNUAL NON-DISCOUNTED RETURNS, SELECTED COSTS AND CASH FLOWS

A2. In-Bin Counterflow Drying (15,000 bushels) (150 bu/hr)

1. System operation



Initial moisture content 26.0% (from field)

Intermediate moisture content 18.0% (from dryer)

Final moisture content 15.5% (from bin)

2. Estimated 1980 investment cost

Quantity	Item	Cost ($)
1	Shivvers performance package	13,921.00
1	Bee's-wing eliminator	1,406.00
1	35 ft. horizontal transport auger (4")	1,540.00
1	18 ft. diameter bin	1,929.00
1	Perforated floor (dryer)	873.00
3	24 ft. diameter bin	9,552.00
3	Perforated floor (24 ft.)	4,665.00
3	Concrete (24 ft. bin)	2,520.00
1	Concrete (18 ft. bin)	750.00
1	Grain spreader	400.00
1	Grain cleaner	600.00
1	Unloading auger + motor (6")	457.00
1	Sweep auger + motor	298.00
1	42 ft. auger + motor	2,050.00
3	Axial fan (.5" SP & 2,500 cfm)	978.00
1	Moisture tester	220.00
	Electrical	2,000.00
	Total investment at list prices	44,159.00
	Less 10% discount	39,743.00
	Installation	1,000.00
	Miscellaneous (2% total investment)	975.00
	TOTAL COST OF THE SYSTEM	$41,538.00

3. Estimated salvage value at the end of 10 years

Bins	\$5,740.00
Perforated floors	2,769.00
Concrete	1,635.00
Electrical	1,000.00
Miscellaneous	397.00
Installation	500.00
Total	\$12,041.00

at 50% salvage cost = \$6,020.00

% salvage of total investment = \$6,020.00 ÷ \$41,538.00 ≈ 14%

4. Estimated annual rate of interest on loan

   7.8% per year

5. Estimated direct energy cost

   \$6.90/100 bushels

6. Estimated indirect energy cost

   \$1.00/100 bushels

7. Estimated labor cost

   \$2.67/100 bushels

8. Estimated maintenance cost over 10 years

   \$41,538.00 x 5% = \$2,076.00 (in 10 years)

Table 21: General economic analysis for a 10-year period for the in-bin counterflow drying system.

YR	TOTAL RETURNS	DEPREC-IATION	PRINC+ INT.	REPAIRS	FUEL+ LUB.	LABOR	SUP-PLIES	AFTER-TX CASH FLW
1	5701	7128	2989	140	1460	465	0	5498
2	6043	6882	6871	203	1577	493	0	-1904
3	6406	5506	6871	246	1703	522	0	-2164
4	6790	4404	6871	284	1839	554	0	-2368
5	7198	3524	6871	320	1986	587	0	-2530
6	7630	2819	6871	356	2145	622	0	-2657
7	8087	2255	6871	391	2317	655	0	-2758
8	8573	1804	6871	426	2502	699	0	-2838
9	9087	1443	4185	462	2702	741	0	-126
10	9632	1155	0	499	2919	785	0	4075
TOTALS	75147	36920	55271	3327	21150	6127	0	-7772

1. ECONOMIC SAVINGS (DISCOUNTED DOLLARS) OVER PEROID OF USE
   IF INVESTMENT IS MADE = $ -8.

2. NUMBER OF UNITS ON WHICH ANALYSIS WAS MADE = 378.

3. DEPRECIATION METHOD USED IN ANALYSIS = 4.

4. ANNUAL NON-DISCOUNTED RETURNS, SELECTED COSTS AND CASH FLOWS

A3. Batch-Low Temperature Combination Drying (15,000 bushels) (228 bu/hr)

1. System operation

From field ⟶ Moisture tester

↓

Grain cleaner

↓

Flight auger

↓

Wet holding tank

↓

Batch dryer ⟶ Moisture tester

↙ ↓ ↘

5,000 bu. bin   5,000 bu. bin   5,000 bu. bin

Initial moisture content 26% (from field)

Intermediate moisture content 22% (from dryer)

Final moisture content 15.5% (from bin)

2. Estimated 1980 investment cost

Quantity	Item	Cost ($)
1	Batch dryer (120 bu/hr)	$ 8,170.00
3	24 ft. diameter bin	9,552.00
3	Perforated floor	4,655.00
1	Wet holding tank	2,235.00
3	Concrete (24 ft. bin)	2,520.00
1	Grain spreader	400.00
1	Grain cleaner	600.00
1	Unloading auger + motor	457.00
1	Sweep auger + motor	298.00
1	42 ft. auger + motor (6")	2,050.00
1	17 ft. auger + motor (6")	750.00
1	Flight auger + motor	3,500.00
3	Tube axial fan (1.5" SP & 7500 cfm)	2,640.00
3	Electrical heater (20 Kwh)	1,560.00
1	Electrical (wiring)	1,000.00
1	Moisture tester	220.00
	Total investment at list prices	40,617.00
	Less 10% discount	36,555.00
	Installation	1,000.00
	Miscellaneous (2% total investment)	731.00
	TOTAL COST OF THE SYSTEM	$38,286.00

3. Estimated salvage value at the end of 10 years

Bins	$ 5,893.00
Perforated floor	2,332.00
Electrical	500.00
Concrete	1,260.00
Miscellaneous	365.00
Installation	500.00
Total	$10,850.00

at 50% salvage cost = $5,425.00

% salvage value total investment = $5,425.00 ÷ $38,286.00 ≈ 14%.

4. Estimated annual rate of interest on loan

   7.8% per year

5. Estimated direct energy cost

   $13.5/100 bushels

6. Estimated indirect energy cost

   $1.00/100 bushels

7. Estimated labor cost

   $1.75/100 bushels

8. Estimated maintenance cost

   $1,914.00 in 10 years

Table 22: General economic analysis for a 10-year period for the low-temperature combination drying system.

YR	TOTAL RETURNS	DEPREC-IATION	PRINC+ INT.	REPAIRS	FUEL+ LUB.	LABOR	SUP-PLIES	AFTER-TX CASH FLW
1	6627	6857	2755	133	2676	357	0	5230
2	7024	6286	6333	191	2890	378	0	-1710
3	7446	5029	6333	231	3121	401	0	-1962
4	7893	4023	6333	267	3371	425	0	-2166
5	8366	3218	6333	300	3641	450	0	-2335
6	8868	2575	6333	333	3932	477	0	-2476
7	9400	2060	6333	366	4246	506	0	-2596
8	9964	1648	6333	398	4586	536	0	-2701
9	10562	1318	3857	432	4953	568	0	-236
10	11196	1055	0	466	5349	602	0	3595
TOTALS								
	87346	34069	50943	3117	38765	4700	0	-7357

1. ECONOMIC SAVINGS (DISCOUNTED DOLLARS) OVER PEROID OF USE IF INVESTMENT IS MADE = $ 3.

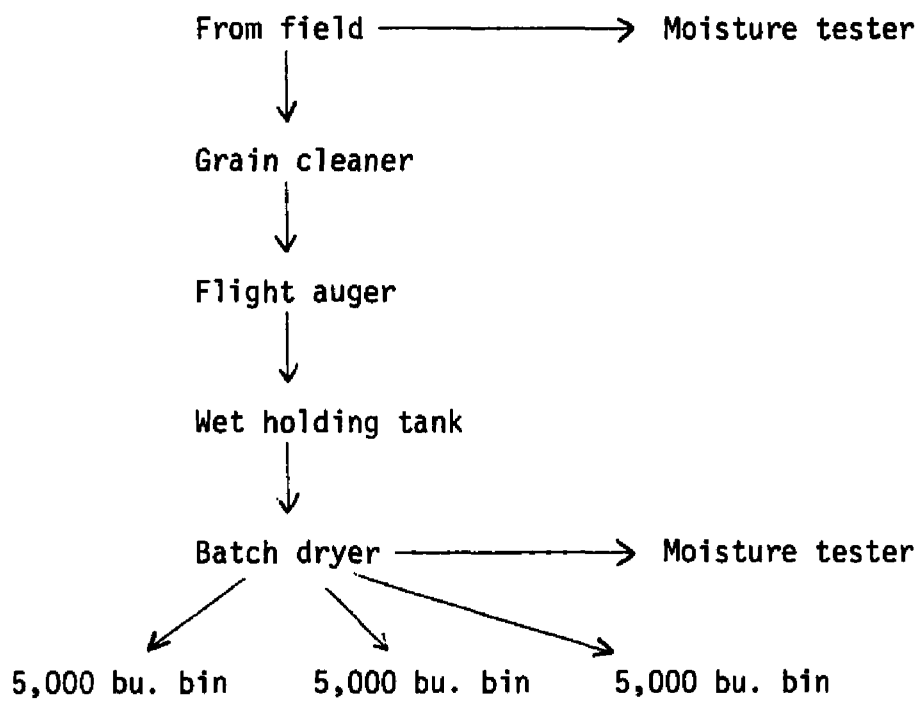
2. NUMBER OF UNITS ON WHICH ANALYSIS WAS MADE = 378.

3. DEPRECIATION METHOD USED IN ANALYSIS = 4.

4. ANNUAL NON-DISCOUNTED RETURNS, SELECTED COSTS AND CASH FLOWS

A4. Batch-Natural Air Combination Drying (15,000 bushels) (288 bu/hr)

1. System operation



Initial moisture content 26% (from field)

Intermediate moisture content 22% (from dryer)

Final moisture content 15.5% (from bin)

2. Estimated 1980 investment cost

Quantity	Item	Cost ($)
1	Batch dryer (120 bu/hr)	$ 8,170.00
3	24 ft. diameter bin	9,552.00
3	Perforated floor	4,665.00
1	Wet holding tank	2,235.00
5	Concrete (24 ft. bin)	2,520.00
1	Grain spreader	400.00
1	Grain cleaner	600.00
1	Unloading auger + motor	457.00
1	42 ft. auger + motor (6")	2,050.00
1	Sweep auger + motor	298.00
1	17 ft. auger + motor (6")	750.00
1	Flight auger + motor	3,500.00
3	Centrifugal fan (2" SP & 10,000 cfm)	4,950.00
	Electrical (wiring)	1,000.00
1	Moisture tester	220.00
	Total investment at list prices	41,367.00
	Less 10% discount	37,230.00
	Installation	1,000.00
	Miscellaneous (2% total investment)	744.00
	TOTAL COST OF THE SYSTEM	$38,274.00

3. Estimated salvage value at the end of 10 years

Bin	$5,893.00
Perforated floor	2,332.00
Electrical	500.00
Concrete	1,260.00
Miscellaneous	346.00
Installation	500.00
Total	$10,831.00

at 50% salvage cost = $5,415.00

% salvage value of total investment = $5,415.00 ÷ $36,332.00 ≈ 15%

4. Estimated annual rate of interest on loan

   7.8% per year

5. Estimated direct energy cost

   $10.4/100 bushels

6. Estimated indirect energy cost

   $1.00/100 bushels

7. Estimated labor cost

   $1.75/100 bushels

8. Estimated maintenance cost

   $1,948 in 10 years

Table 23: General economic analysis for a 10-year period for the natural-air combination drying system.

YR	TOTAL RETURNS	DEPREC-IATION	PRINC+ INT.	REPAIRS	FUEL+ LUB.	LABOR	SUP-PLIES	AFTER-TX CASH FLW
1	6014	6914	2804	135	2103	357	0	5231
2	6375	6412	6447	194	2272	378	0	-1805
3	6757	5130	6447	235	2453	401	0	-2057
4	7162	4104	6447	271	2649	425	0	-2260
5	7592	3283	6447	305	2861	450	0	-2424
6	8048	2626	6447	338	3090	477	0	-2559
7	8531	2101	6447	371	3338	506	0	-2671
8	9043	1681	6447	404	3605	536	0	-2766
9	9585	1345	3926	438	3593	568	0	-244
10	10160	1076	0	473	4204	602	0	3672
TOTALS	79267	34672	51859	3164	30468	4700	0	-7883

1. ECONOMIC SAVINGS (DISCOUNTED DOLLARS) OVER PEROID OF USE
   IF INVESTMENT IS MADE = $ -1.

2. NUMBER OF UNITS ON WHICH ANALYSIS WAS MADE = 378.

3. DEPRECIATION METHOD USED IN ANALYSIS = 4.

4. ANNUAL NON-DISCOUNTED RETURNS, SELECTED COSTS AND CASH FLOWS

A5. In-Bin Dryeration Drying (15,000 bushels)
(170 bu/hr)

1. System operation

↓

From field → Moisture tester

↓

Grain cleaner

↓

Flight auger

↓

Wet holding tank

↓

Batch dryer

↙ ↓ ↘

5,000 bu. bin   5,000 bu. bin   5,000 bu. bin

↘ ↓ ↙

10 hours tempering

↓

aeration

Initial moisture content 26% (from field)

Intermediate moisture content 19% (from dryer)

Final moisture content 15.5% (from bin)

2. Estimated 1980 investment cost

Quantity	Item	Cost ($)
1	Batch dryer (120 bu/hr)	$ 8,170.00
3	24 ft. diameter bin--12 ft. ht.	9,552.00
3	Perforated floor	4,665.00
1	Wet holding tank (800 bu)	2,235.00
3	Concrete	2,520.00
1	Grain spreader	400.00
1	Grain cleaner	600.00
1	Sweep auger	298.00
1	Unloading auger + motor	457.00
1	42 ft. auger + motor (6")	2,050.00
1	17 ft. auger + motor (6")	750.00
3	Tube axial fan (1" SP & 5,000 cfm)	2,070.00
	Electrical	1,000.00
1	Moisture tester	222.00
~~1~~	Flight auger + motor	3,500.00
	Total investment at list prices	38,489.00
	Less 10% discount	34,640.00
	Installation	1,000.00
	Miscellaneous (2% total investment)	692.00
	TOTAL COST OF THE SYSTEM	$36,332.00

3. Estimated salvage value at the end of 10 years

Bins	$5,893.00
Perforated floor	2,332.00
Concrete	1,260.00
Electrical	500.00
Miscellaneous	346.00
Installation	500.00
Total	$12,041.00

at 50% salvage cost = $6,020.00

% salvage value of total investment = $5,415.00 ÷ $35,332.00 ≈ 15%

4. Estimated annual rate of interest on loan

   7.8% per year

5. Estimated direct energy cost

   $7.00/100 bushels

6. Estimated indirect energy cost

   $1.00/100 bushels

7. Estimated labor cost

   $2.35/100 bushels

8. Estimated maintenance cost

   $1,816.00 in 10 years

Table 24: General economic analysis for a 10-year period for the in-bin dryeration system.

YR	TOTAL RETURNS	DEPREC-IATION	PRINC+ INT.	REPAIRS	FUEL+ LUB.	LABOR	SUP-PLIES	AFTER-TX CASH FLW
1	5176	6694	2614	129	1479	425	0	4921
2	5487	5928	6010	184	1597	450	0	-1723
3	5816	4742	6010	223	1725	477	0	-1949
4	6165	3794	6010	256	1863	506	0	-2129
5	6535	3035	6010	288	2012	536	0	-2273
6	6927	2428	6010	319	2173	568	0	-2388
7	7343	1942	6010	350	2347	602	0	-2481
8	7783	1554	6010	382	2534	639	0	-2557
9	8250	1243	3660	414	2737	677	0	-192
10	8746	994	0	446	2956	718	0	3474
TOTALS	68228	32354	48344	2991	21423	5598	0	-7297

1. ECONOMIC SAVINGS (DISCOUNTED DOLLARS) OVER PEROID OF USE IF INVESTMENT IS MADE = $ 8.

2. NUMBER OF UNITS ON WHICH ANALYSIS WAS MADE = 378.

3. DEPRECIATION METHOD USED IN ANALYSIS = 4.

4. ANNUAL NON-DISCOUNTED RETURNS, SELECTED COSTS AND CASH FLOWS

APPENDIX B

THE FARMER'S POINT OF VIEW

THE FARMER'S POINT OF VIEW

The following statements about the five alternative drying techniques and related equipment were made by Stephen Kalchik, co-owner of the Kalchik Farms, Bellaire, Michigan. The writer feels that Mr. Kalchik's experience with the system will give important help in the decision to adopt any of the studied drying systems.

"Much more is involved with the operation of these systems than fuel costs and depreciation schedules. Farmers should be encouraged to use systems that are most profitable in the long run for their particular circumstances. Potential grain spoilage losses and management expertise should also be major considerations.

Automatic batch dryers were the logical first choice during the era of inexpensive fossil fuels. Much flexibility is possible, operation is relatively easy, and expansion or replacement of the equipment is not difficult. Installation of fuel and electrical components is similar for all models of comparable size. Initial control settings are predictable from the operator's manual, and output is fairly consistent. No extra time is required to clean the grain because the cleaner is sized to the transport conveyors. A dependable electronic moisture tester is required for this system and all others listed to produce the best results.

Overdrying is a major problem. Farmers should be encouraged to sell as much water as possible. Fire can be a problem because of the high temperature in automatic batch dryers and dust generated at grain-handling sites.

Storage of the equipment during the off season may be indoors to prolong life. Many automatic batch dryers can be moved in less than one hour. Serviceability is very good. The operator must pay close attention to the moisture content of grain delivered to the bin from the automatic batch dryer, grain temperature, and time the grain 'steeps' before the cooling fans are switched on during each production interval. Benefits from fuel saved more than offset the additional time required. Conversion to in-bin dryeration is relatively simple and can make good use of an existing automatic batch-drying system.

The operator must have instrumentation for relative humidity measurements. Automatic humidistats are not dependable and require frequent calibration. Continuous use of the low-temperature heater will result in severe overdrying of the lower grain in some years. During years of low relative humidity, use of a stirring device will reduce the MC gradient in the bin. Continuous operation is not necessary. This system requires daily attention.

Excellent grain quality is possible with low-temperature systems.

Natural-air systems are comparable to LT in management. In poor years natural-air systems may fail first, especially if warm, humid weather occurs for a prolonged period.

In-bin counterflow drying offers some of the same advantages as automatic batch drying. Operation is dependable and consistent.

Grain of any moisture content can be dried. However, very little flexibility is allowed during operation. Typically, the installation is permanent and an integral part of the storage site. Since more electrical wiring is required on site, the operator must have a better understanding of the working details of this system. Fuel consumption compares favorably with the in-bin dryeration using the automatic batch dryer, but the in-bin counterflow is much easier to manage.

A vacuum apparatus was installed to remove BCFM from the dried grain moving to storage. When BCFM increased to high levels (such as 25%) because of high initial moisture and combine damage, the vacuum system did not perform satisfactorily. During wet weather the exhausted material actually blocked the vacuum blower exhaust port due to condensation. However, during normal operation with inlet grain below 30%, the cleaning system performed well.

Most of the components of an in-bin counterflow system are field installed, so the performance of this system is directly related to proper installation. It can be a very good system. The author felt quite comfortable leaving it on automatic all night.

All grain should be cleaned prior to drying by any system to allow better airflow. A grain cleaner can be selected to run at the capacity of the transport equipment. The cleanings should be fed to livestock promptly because of high moisture content. This material is not a loss when used for feed. The friction drive on the grain cleaner used at this test site did not function effectively in snow and rain. In dry weather conditions it was 100% effective on fine materials.

Labor requirements are highest for the low-temperature and natural-air systems, lowest for the automatic batch and in-bin counterflow, and in-bin dryeration falls in the middle."

APPENDIX C

TELPLAN 03 USER'S GUIDE

CAPITAL INVESTMENT MODEL--INCLUDING BUY OR CUSTOM HIRE
A TELPLAN PROGRAM

Date: January 15, 1972
Developed by: Stephen B. Harsh
Department of Agricultural Economics
Michigan State University

Number: 03
Form: 3
System: Touch-Tone Phone

Objective:

To evaluate the investment of capital to reduce or eliminate costs including custom hire and leasing, or to generate new income.

Description:

This model can be used to evaluate numerous types of investment decisions. It is particularly useful in evaluating investment of capital in buildings and/or equipment to perform an operation previously done on a custom basis. It can also be used to evaluate investment decisions on such items as a new type of hog system, a new milk house--parlor facility or any other new technology which replaces the existing technology. Furthermore, it can also be used to evaluate the economics of investing in new technology to generate new income or to better fulfill the firm manager's goals.

Assumptions of the Model:

The validity of answers derived from this model depends heavily on the quality of the input information supplied. However, a number of assumptions are made by the model. These assumptions are detailed in later sections (Page 03:5 [F3] and Page 03:6 [F3]) and the user has the option of overriding any of these assumptions if he feels that a more realistic answer would be obtained if an assumption was modified.

Computational Procedures Used in the Analysis:

Budgeting and discounted cash flows.

Explanation of Input Data:

Section I. Cost Reducing (Custom Hire or Leasing) or Income Producing Information.

This section of the input form relates to those costs that will be eliminated or reduced (or income generated) if the investment is made. In addition, this section indicates the intensity of use of the investment.

1a. Enter the savings in costs (or income generated) per unit for a certain class of expenses (or income).

Example A--Buy Versus Custom Hire: A farmer is considering the purchase of a combine to replace a custom operation. He would enter the custom cost (e.g., $9.00 per acre) which is a reduction in costs.

Example B--Cost Reducing Investment: A farmer is considering the purchase of a new milking parlor which will eliminate labor needed for the milking operation. He would enter the dollars labor saved (e.g., $60.00 per cow annually).

Example C--Income Generating Investment: A farmer is considering the expansion for his swine finishing facility. He would enter the profit (e.g., $4.00 per head annually). Profit in this case is defined as returns per head less costs per head (feed cost, labor, feeder pigs, etc., but excluding the costs associated with the investment).

2a. Enter the savings in costs (or income generated) per unit for a second class of expenses (or income). NOTE: It is not necessary for you to use this input line. However, it is included to allow evaluation of reduced costs (or generated income) that have different characteristics (e.g., different inflation rates) than those included in input line 1a.

Example A--Buy Versus Custom Hire: It is suggested that the user enter the additional annual losses associated with custom hire which in reality is new income generated. In the combine example, enter the dollar value (e.g., $4.00 per acre annually) of lost yields due to poor timing or carelessness of the custom operator. In some cases, this value may be negative; if this is the case, enter the value as such. A point of caution, additional losses associated with custom hire are important to the economics of the investment. If the farmer is uncertain of the magnitude of these losses, you are encouraged to do adjusted analyses which cover the possible range of these losses.

Example B--Cost Reducing Investment: In the milking parlor example, the farmer feels that he may experience a minor drop in milk production. This input line can be used to enter this information. Since a drop in milk production is not an increase in income but actually a decline in income, this value (e.g., -$6.00 per cow annually) would be entered with a negative sign.

Example C--Income Generating Investment: The farmer that has plans to expand his swine operation has included all the income generated in the first line and, therefore, chooses to enter a zero in this line.

3a. Enter the number of units on which costs will be reduced (or income generated).

Example A--Buy Versus Custom Hire: Since the cost savings and income produced for the combine as indicated in input lines 1a and 2a was stated in dollars per acre, you should indicate the number of acres you expect to harvest with the combine (e.g., 300 acres).

Example B--Cost Reducing Investment: In the milking parlor case, you should enter the average number of cows in milk (e.g., 100 cows) that will utilize the parlor annually.

Example C--Income Generating Investment: Using the swine facility as an example, you should enter the number of head (e.g., 400 head) that will pass through the facility annually.

3b. Enter the percent of the units indicated in 3a that will be absorbed by investment in the first year of purchase. This input is included to allow you to adjust for investments made in different times of the year. For example, if a machine may have been purchased early in the year and full use made of it during the year, enter "100". If a machine was purchased in the later part of the year for tax purposes with no opportunity for utilization, a value of zero would be entered. If a machine is purchased midseason, the appropriate percentage should be used.

Section II. Investment Information.

This section is used to enter information regarding the investment being considered.

4a. Enter the total dollar cost including the undepreciated balance of trade-in items. Be sure to consider all costs (e.g., installation costs, shipping costs, etc.).

4b. Enter the percent of the undepreciated value of trade-in items that are of total cost. To compute this value, divide the undepreciated value of trade-in items by the value entered in input 4a and multiply the result by 100.

5a. If you are considering a used item, it is essential to make an estimate of the cost of this investment when it was new. This figure is correlated with the present value and is used to determine the degree of wear on the machine. This, in turn, will affect the repair costs assumed by the model. If a new item is being purchased, enter the same value entered in 4a in this input item. In addition, this input value indicates whether the investment is a new or used item, which will affect depreciation methods used in the analysis.

5b. Enter the number of years you plan to use the investment.

6a. Enter the number of years that the investment would be depreciated over. Years must be less than or equal to number of years that investment will be used (input line 5b). If a non-depreciable item, enter "00".

6b. Enter the salvage percentage to be used. Salvage percent should reflect the estimated market value of investment at the end of the period of use. This percentage should be entered even for non-depreciable items. For depreciation purposes, the computer will automatically deduct 10 percent from this value because this is allowable under depreciation regulations.

6c. Enter the month purchased. January would be quoted as 01; February 02; March 03; etc. This code indicates to the computer what proportion of the first year's depreciation should be allocated to the machine and adjusts the first year's loan and interest payments.

6d. Indicate the type of depreciation that will be used in the analysis. If you want the model to choose the best depreciation method, enter zero. However, caution should be expressed at this point. The model may select a depreciation method that is not allowable for your particular type of investment. If this happens, you should override the method selected by forcing the model to use an appropriate depreciation method and recompute the answers.

6e. Indicate whether or not the machine is eligible for investment tax credit, as detailed in the tax regulations. If eligible, enter a "1", if not, enter "0".

7a. If a loan is to be obtained in the purchase of this investment, enter the percent the loan is of the total cost. This figure can be computed by dividing the size of the loan by input line 4a and multiplying the result by 100.

7b. Indicate the loan repayment period in years. Number of years must be less than or equal to the years of use for investment (input line 5b).

7c. Enter the annual rate of interest (percent) payable on the loan.

8a. Indicate the per hour fuel cost of operating the investment.[1,2] Be sure to adjust cost to account for the gas tax refund. This figure should include only the fuel cost of operating the investment itself and not the fuel cost of operating any associated equivalent used in conjunction with the investment (e.g., the gas needed to operate the tractor which is pulling a forage chopper, the investment being considered, would not be included in this figure but would be included in the input line 8b).

To estimate fuel consumption the following equations can be used:

Gasoline consumption (Gal/Hr.) = .06 X Horsepower of engine.
Diesel consumption (Gal/Hr.) = .048 X Horsepower of engine.
L.P. consumption (Gal/Hr.) = .072 X Horsepower of engine.

To estimate electricity consumption the following equation can be used:

(KHR/Hr.) = 0.9 X Horsepower of motor.

NOTE: For input line 8a and 8b lubrication cost (oil & grease) is automatically added to the fuel costs (see Page 03: [F3]).

8b. Enter the per hour fuel cost of operating the associated equipment used in conjunction with the investment.[3] This figure is collected separately from the fuel costs of operating the investment because an assumption is made regarding the additional repairs incurred on this equipment. The method used to compute the additional repair costs is explained in Table 1 of the input form (Page 03:).

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[1]In entering these costs, it is important to bear in mind that you should include only those costs that are in addition to those previously provided. For example, a farmer who was having his silage custom harvested also furnished a tractor and a man for the operation. He is now considering the purchase of a new forage harvester. To operate his own harvester, he has to have three tractors and two men. For the purpose of this analysis, he would only be concerned about the costs of the additional man and two tractors. In our milking parlor example, which was discussed in earlier input lines, you would only include those costs that will be higher than those experienced under the old milking system.

[2]See preceding page.

[3]Refer to footnote 1.

9a. Enter the per hour labor cost of operating the investment and associated equipment.[1] Labor costs should include wages paid, social security, workman's compensation, fringe benefits, etc.

9b. Enter the per hour cost of supplies in operating the investment and associated equipment.[1]

10a. This input line is used to indicate repairs costs on the investment. If you have little knowledge of the level of repairs that might be incurred on the investment, it is suggested that you select one of the types of machines indicated on the input form and the model will estimate the repairs for the machine over its life based on its level of usage. Repair costs estimated by this means will include both the cost of the repairs and a value for the labor used in making the repairs. <u>NOTE</u>: When using the computer to estimate repairs, it is <u>essential that</u> input lines 8a, 8b, 9b and 11 be stated on a per hour basis. If the repairs that are estimated by the model appear to be unrealistic, or you have a good estimate of what repairs will be, or you are unable to match his investment with those listed, you can enter the estimated repair cost over the period in today's dollars. The model will use this amount as a base and make adjustments for inflation over time.

11a. This factor is used to correlate per hour[2] usage figures indicated in lines 7a through lines 9b with the units discussed in the first section of the input. Indicate the number of units that can be handled per hour. For machinery used in field operations, the following formula may be useful in figuring the number of acres per hour that can be handled by the machine.

Field Capacity (AC/HR) =

$$\frac{\text{Speed (MPH) X Width of Machine (ft) X Field Eff. (\%)}}{825}$$

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[1]Refer to footnote 1 on previous page.

[2]The costs in lines 8a, 8b, 9a, 9b and the conversion factor in line 11a are expressed on a per hour basis. For some types of investments, the use of hours as a common denominator for costs is not logical. Such a case exists in our swine finishing facility example which was discussed in earlier input lines. It is possible for you to use another measure as long as you are consistent. For example, you could express the swine finishing costs on a per year basis (e.g., $2,000 labor costs per year) rather than on a per hour basis. In addition, the value in line 11 would also be stated on the same per year basis. In this case, the number of units (head) that can be handled per year is 400 which is the same value entered in input value 3a.

Selected Field Efficiencies (Average Values)	
Tillage Operations	85%
Plant Fertilizer Crop	60%
Combining	70%
Chop Silage	60%

Section III. Federal Tax, Rate of Return and Cash Flow Information.

Taxes are considered because the tax laws have a significant effect on the economics of various investments. The rate of return is also a critical value. Cash flow information is collected because some investments may be economically profitable, but because of liquidity problems of some firms, they are still unable to justify the investment.

12a. Enter the estimated tax bracket faced in the year of purchase.

12b. Enter the estimated tax bracket in the first one-half year of the investment following the first year.

12c. Enter the estimated tax bracket for the last half of the investment.

13a. Indicate the desired percentage rate of return on the investment for the first one-half years of investment. When considering the rate of return on investment, it should be at least equal to what the money can earn when used in other good investments. It is important that the rate used be above the after-tax cost of money (after-tax cost of money is equal to interest rate of loan multiplied by one minus the tax rate) of existing loans plus some amount to reflect risk.

13b. Indicate the desired return on investment during the last one-half years of the investment. The rate of return information is collected in two parts. This relates to those investments of long length. A situation in which a young businessman's liquidity problem is high in the early years of the investment, but as time passes money becomes much easier to acquire and the demands upon it less critical. Therefore, a lower rate of return should be used in the later period.

13c. The user should indicate that size of loan (thousands of dollars) in annual principle and interest payments the current business can withstand. This value is used to determine if the investment will cause liquidity problems for the business. The investment may be a very good one from an economic viewpoint but because of the loan taken, it may run into liquidity problems which may be disastrous for the business.

Section IV: Modification of Assumptions:

A number of assumptions are made by the computer model which in most cases results in a more accurate analysis of the situation. These assumptions are detailed in Table 1. However, there may be situations in which different assumptions would yield a more accurate analysis. In this case, it is possible for you to override the values assumed by the model and replace them with more appropriate values.

Table 1. VALUES ASSUMED BY MODEL

Assumption Code	Assumed Value	Definition
01.	0.0	To determine or not determine break-even units--When the value is set to zero the model will attempt to find the break-even units of usage, if usage level entered in line 3a is not large enough to make investment profitable. When set to 1.0, the model will not attempt to find break-even and will state actual losses or gains for usage level entered in line 3a.
02.	2.7	Annual percentage rate of inflation on the costs saving (or income generated) indicated in line 1a. The value assumed (2.7%) is the appropriate inflation rate for custom costs.
03.	0.0	Annual percentage rate of inflation on the cost savings (or income generated) indicated in line 2a. A value of 0% has been assumed because, in many cases, this will closely approximate the inflation rate for additional losses associated with custom hire.
04.	6.0	Labor cost annual percentage rate of inflation.
05.	1.9	Fuel and oil costs annual percentage rate of inflation.
06.	4.0	Repair costs annual percentage rate of inflation.
07.	1.3	Supplies cost annual percentage rate of inflation.

Table 1. (cont'd.)

Assumption Code	Assumed Value	Definition
08.	4.0	New machine purchase cost annual percentage rate of inflation (affects salvage value).
09	0.7	Insurance cost* as a percentage of the beginning inventory value for each year.
10.	0.5	Housing cost* as a percentage of the beginning inventory value for each year.
11.	15.0	Oil and lubrication cost as a percentage of fuel cost.
12.	35.0	Associated equipment's repairs cost as a percentage of associated equipments fuel cost.
13.	0.0	Annual percentage rate of increase in the use of the investment.

*NOTE: Personal property tax can be included by raising this percentage value upward.

For example, you feel that the inflation rate for labor costs (Assumption Code 04) in your area will be somewhat less than the six percent assumed by the model. If you desire to override the six percent rate and replace it with a four percent rate, you should enter information as indicated below:

14a. Assumption Value Desired　　14. |0 4 . 0 |0 4|
b. Assumption Code

15a. Assumption Value Desired　　15. |_ _ . _ |_ 0|
b. Assumption Code

Input line 15 was coded zero in above examples to indicate end of assumption changes.

Error Messages Relating to Erroneous Input Data.

Line 3. The value for line 3a has to be greater than 0.

Line 5. If the number of years (line 5b) is greater than 25, an error message will be given also if less than two years.

Line 6. The maximum number of years for depreciation cannot exceed that value entered in line 5b.

Line 7. The number of repayment years of the loan cannot exceed the number of years of the investment (input line 5b). Error messages will also be given if repayment years of loan is zero or the rate of interest is zero when there is a loan indicated in line 7a.

Line 10. An error is given if you try to use a nonexistent type of machine code or the estimated dollars of repair costs is less than $25.

Lines 14-20. You are given an error message if you use an assumption code that does not exist.

Explanation of Output:

Line 1 This value gives the economic evaluation of the investment in discounted dollars over the entire period of use. If this value is positive, then the investment is an economic one, and serious consideration should be given to making the investment. However, it should be stressed that the answers are dependent upon the input values entered into the model and, therefore, are only as good as the input data.

Line 2 Output value 2 indicates the number of units in which the analysis was made. If the number of units exceed the values inputted in 3a, and the savings indicated in line 1 is zero, then the answer indicates the break-even point of the analysis (NOTE: If this value is approximately 4 times the size of that entered in input line 3a and result 1 is a large negative value, this usually indicates that the input data was erroneous or this is a very uneconomic investment).

Line 3 The value given depends on whether you have specified a certain type of depreciation method. If you indicate the depreciation method to be used, this value is given and is the same as entered in the input section. If the model selects the best depreciation value, the results obtained from the model are based on this depreciation method and using an alternative depreciation method will decrease the economic advantage of this investment. However, if the model should select a depreciation method not allowable under the tax regulations, you should specify an alternative depreciation method (see information relating to input value 6d, page 03:4 [F3]).

Line 4 — The first part of this answer indicates the total repairs costs (nondiscounted dollars) of the investment over its life of use. The repair cost of the associated equipment used in conjunction with your equipment is also included in this value. If this repair cost appears to be an unrealistic value, adjustments can be made. The procedure for this is explained in the input section under value 10, page 03:6 (F3). The second part of the answer indicates the fuel and lubrication costs in nondiscounted dollars of using the investment over the entire period. The fuel and lubrication costs are for both the investment itself and the equipment used in conjunction with the investment.

Line 5 — Output line 5 indicates the nondiscounted dollars labor costs over the life of investment and the second part of the answer contains the supply costs in nondiscounted dollars over the life investment.

Line 6 — The first part of the answer indicates the number of years that cash flow problems will be encountered over the life of investment. The second part of the output line indicates the magnitude of the cash flows in the worst year. If the first answer is zero and the second answer positive, this indicates that this investment does not have cash flow problems. However, if the first answer is positive and the second answer negative, this indicates that the investment will run into cash flow problems and the user must evaluate whether these cash flow problems are significant enough to discourage him from making an investment. The larger the negative answer, the more difficult the cash flow problem.

Program No: 03
Form No: 3
System: TOUCH-TONE PHONE

CAPITAL INVESTMENT MODEL -- INCLUDING BUY OR CUSTOM HIRE
A TELPLAN PROGRAM

NAME Batch Drying ADDRESS

PHONE DATE RUN

Problem: To evaluate the investment of capital to reduce or eliminate costs including custom hire and leasing, or to generate new income.

INPUT: LINE NO. ADJUSTED ANALYSIS

Section I. Costs Reducing (Custom Hire Or Leasing) Or Income Producing Information.

		LINE NO.	ADJUSTED ANALYSIS
1a.	Cost savings (or income produced) per unit* for a certain class of expenses (or income). For example, custom rate per unit ($)	01. 015.82	
2a.	Cost savings (or income produced) per unit* for a second class of expenses (or income). For example, additional per unit annual losses associated with custom hire ($)	02. -001.80	
3a.	Normal number of units* per year on which costs will be reduced (or income generated).	03. 000378	
b.	Percent of units* indicated in Line 3a that will be absorbed by investment in the year of purchase.	100	

Section II. Investment Information.

		LINE NO.	ADJUSTED ANALYSIS
4a.	Total dollar cost including undepreciated balance of trade-in items.	04. 035126	
b.	Percentage undepreciated value of trade-in items is of total cost.	00	
5a.	If a used item enter estimated new cost of item. If new item enter same value entered in Line 4a.	05. 035126	
b.	Years plan to use the investment.	10	

* It is very important to be consistent in your units. (For example, if the custom rate is stated on acres all the other units are also to be stated in acres).

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		LINE NO.	ADJUSTED ANALYSIS
6a.	Depreciation years	06. 1 0 1 5 0 8 4 1	
b.	Salvage percent		
c.	Month of purchase (01=Jan,....., 12=Dec.).		
d.	Depreciation type (0=Have model choose best depreciation method to use; 1=Straight line; 2=Straight line with additional 20%; 3=Double decline balance; 4=Double decline balance with additional 20%; 5=1.5 decline balance; 6=1.5 decline balance with additional 20%; 7=Sum-of-digits; 8=Sum-of-digits with additional 20%).		
e.	Does investment qualify for investment credit (0=no; 1=yes).		
7a.	Percent of total cost (input line 4a) borrowed.	07. 1 0 0 0 8 0 7 . 8	
b.	Repayment period of loan-years		
c.	Annual rate of interest on loan(%)		
8a.	Per hour^x fuel cost of operating investment** ($)	08. 0 4 . 5 3 0 0 . 3 9	
b.	Per hour^x fuel cost of operating associated equipment** ($)		
9a.	Per hour^x labor cost of operating investment & associated equipment.	09. 0 4 . 8 0 0 0 . 0 0	
b.	Per hour^x cost of supplies of operating investment & associated equipment.		
10a.	Repairs costs of investment: Enter estimated repairs costs over period or use in today's dollars (amount must exceed $25) OR enter type*** of machine to have model estimate repairs costs. Types of machines are: 1=tractors; 2=Self-P. Combine, Self-P. Forage harvester, Rotary Cutter; 3=Pull type combine. Pull type forage harvester, Flail harvester; 4=Self-P. swather, Self-U.L. Wagon, Side D. Rake; 5=Fertilizer equip; 6=Potato harvester, Sugar beet harvester, PTO Bailer; 7=Tillage tools, Mower; 8=Seeding equip; Boom sprayers; 9=truck; 10=Air Blast Sprayer.	10. 0 1 7 5 6	
11a.	Number of units* handled per hour^x	11. 0 0 0 1 . 0 0	

* Refer to Page 1

** See instructions for Program 03, Form 3 for suggested guidelines.

*** If you cannot find your machine in the list, try to match to a machine that is similar or enter estimate of repairs costs.

x Hours are used as a measure for expressing costs in lines 8a,8b,9a,9b and as a conversion factor in line 11. You can use a different measure as long as you are consistent in these lines.

	LINE NO.	ADJUSTED ANALYSIS
Section III. Federal Tax, Rate Of Return And Cash Flow Information.		
12a. Tax bracket in year of purchase. b. Tax bracket for first 1/2 years of investment. c. Tax bracket for last 1/2 years of investment.	12. 30 30 30	
13a. Desired percentage rate of return on investment for first 1/2 years of investment. b. Desired percentage rate of return on investment for last 1/2 years of investment. c. Additional debt load (annual principal & interest payment in thousands of dollars) that the current business can withstand.	13. 09 09 000.0	
Section IV. Modification Of Assumptions[xx] (Enter "0" on line following last modification to be made. If none, enter "0" on line 14)		
14a. Assumption value desired b. Assumption code	14. 01.0 01	
15a. Assumption value desired b. Assumption code	15. 06.0 02	
16a. Assumption value desired b. Assumption code	16. 08.0 05	
17a. Assumption value desired b. Assumption code	17. 06.0 08	
18a. Assumption value desired b. Assumption code	18. 01.0 09	
19a. Assumption value desired b. Assumption code	19. 01.6 10	
20a. Assumption value desired b. Assumption code	20. 06.0 03	

xx See instructions for Program 03, Form 3 on how to use this section.

Program No: 03
Form No: 3
System: TOUCH-TONE PHONE

CAPITAL INVESTMENT MODEL -- INCLUDING BUY OR CUSTOM HIRE
A TELPLAN PROGRAM

NAME In-Bin Counterflow ADDRESS

PHONE DATE RUN

Problem: To evaluate the investment of capital to reduce or eliminate costs including custom hire and leasing, or to generate new income.

INPUT: LINE NO. ADJUSTED ANALYSIS

Section I. Costs Reducing (Custom Hire Or Leasing) Or Income Producing Information.

1a. Cost savings (or income produced) per unit* for a certain class of expenses (or income). For example, custom rate per unit ($) — 01. 014.34

2a. Cost savings (or income produced) per unit* for a second class of expenses (or income). For example, additional per unit annual losses associated with custom hire ($) — 02. 001.60

3a. Normal number of units* per year on which costs will be reduced (or income generated). — 03. 000378 | 100
b. Percent of units* indicated in Line 3a that will be absorbed by investment in the year of purchase.

Section II. Investment Information.

4a. Total dollar cost including undepreciated balance of trade-in items. — 04. 041538 | 00
b. Percentage undepreciated value of trade-in items is of total cost.

5a. If a used item enter estimated new cost of item. If new item enter same value entered in Line 4a. — 05. 041538 | 10
b. Years plan to use the investment.

* It is very important to be consistent in your units. (For example, if the custom rate is stated on acres all the other units are also to be stated in acres).

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		LINE NO.	ADJUSTED ANALYSIS
6a.	Depreciation years	06. 10 1 4 0 8 4 1	________
b.	Salvage percent		
c.	Month of purchase (01=Jan,...., 12=Dec.).		
d.	Depreciation type (0=Have model choose best depreciation method to use; 1=Straight line; 2=Straight line with additional 20%; 3=Double decline balance; 4=Double decline balance with additional 20%; 5=1.5 decline balance; 6=1.5 decline balance with additional 20%; 7=Sum-of-digits; 8=Sum-of-digits with additional 20%).		
e.	Does investment qualify for investment credit (0=no; 1=yes).		
7a.	Percent of total cost (input line 4a) borrowed.	07. 100 08 07.8	________
b.	Repayment period of loan-years		
c.	Annual rate of interest on loan(%)		
8a.	Per hour[x] fuel cost of operating investment** ($)	08. 02.72 00.39	________
b.	Per hour[x] fuel cost of operating associated equipment** ($)		
9a.	Per hour[x] labor cost of operating investment & associated equipment.	09. 01.16 00.00	________
b.	Per hour[x] cost of supplies of operating investment & associated equipment.		
10a.	Repairs costs of investment: Enter estimated repairs costs over period or use in today's dollars (amount must exceed $25) OR enter type*** of machine to have model estimate repairs costs. Types of machines are: 1=tractors; 2=Self-P. Combine, Self-P. Forage harvester, Rotary Cutter; 3=Pull type combine. Pull type forage harvester, Flail harvester; 4=Self-P. swather, Self-U.L. Wagon, Side D. Rake; 5=Fertilizer equip; 6=Potato harvester, Sugar beet harvester, PTO Bailer; 7=Tillage tools, Mower; 8=Seeding equip; Boom sprayers; 9=truck; 10=Air Blast Sprayer.	10. 02076	________
11a.	Number of units* handled per hour[x]	11. 0001.00	________

* Refer to Page 1

** See instructions for Program 03, Form 3 for suggested guidelines.

*** If you cannot find your machine in the list, try to match to a machine that is similar or enter estimate of repairs costs.

x Hours are used as a measure for expressing costs in lines 8a,8b,9a,9b and as a conversion factor in line 11. You can use a different measure as long as you are consistent in these lines.

	LINE NO.	ADJUSTED ANALYSIS
Section III. Federal Tax, Rate Of Return And Cash Flow Information.		
12a. Tax bracket in year of purchase. b. Tax bracket for first 1/2 years of investment. c. Tax bracket for last 1/2 years of investment.	12. 30 | 30 | 30 includes social security	
13a. Desired percentage rate of return on investment for first 1/2 years of investment. b. Desired percentage rate of return on investment for last 1/2 years of investment. c. Additional debt load (annual principal & interest payment in thousands of dollars) that the current business can withstand.	13. 09 | 09 | 000.0	

Section IV. Modification Of Assumptionsxx
(Enter "0" on line following last modification to be made. If none, enter "0" on line 14)

	LINE NO.	ADJUSTED ANALYSIS
14a. Assumption value desired b. Assumption code	14. 01.0 | 01	
15a. Assumption value desired b. Assumption code	15. 06.0 | 02	
16a. Assumption value desired b. Assumption code	16. 08.0 | 05	
17a. Assumption value desired b. Assumption code	17. 06.0 | 08	
18a. Assumption value desired b. Assumption code	18. 01.0 | 09	
19a. Assumption value desired b. Assumption code	19. 01.6 | 10	
20a. Assumption value desired b. Assumption code	20. 06.0 | 03	

xx See instructions for Program 03, Form 3 on how to use this section.

Program No: 03
Form No: 3
System: TOUCH-TONE PHONE

CAPITAL INVESTMENT MODEL -- INCLUDING BUY OR CUSTOM HIRE
A TELPLAN PROGRAM

NAME In-Bin Dryeration ADDRESS ____________

PHONE ____________ DATE RUN ____________

Problem: To evaluate the investment of capital to reduce or eliminate costs including custom hire and leasing, or to generate new income.

INPUT:

		LINE NO.	ADJUSTED ANALYSIS
Section I. Costs Reducing (Custom Hire Or Leasing) Or Income Producing Information.			
1a.	Cost savings (or income produced) per unit* for a certain class of expenses (or income). For example, custom rate per unit ($)	01. 013.02	________
2a.	Cost savings (or income produced) per unit* for a second class of expenses (or income). For example, additional per unit annual losses associated with custom hire ($)	02. -001.06	________
3a.	Normal number of units* per year on which costs will be reduced (or income generated).	03. 000378 | 100	________
b.	Percent of units* indicated in Line 3a that will be absorbed by investment in the year of purchase.		
Section II. Investment Information.			
4a.	Total dollar cost including undepreciated balance of trade-in items.	04. 036332 | 00	________
b.	Percentage undepreciated value of trade-in items is of total cost.		
5a.	If a used item enter estimated new cost of item. If new item enter same value entered in Line 4a.	05. 036332 | 10	________
b.	Years plan to use the investment.		

* It is very important to be consistent in your units. (For example, if the custom rate is stated on acres all the other units are also to be stated in acres).

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		LINE NO.	ADJUSTED ANALYSIS
6a.	Depreciation years	06. 10 15 08 4 1	________
b.	Salvage percent		
c.	Month of purchase (01=Jan,....., 12=Dec.).		
d.	Depreciation type (0=Have model choose best depreciation method to use; 1=Straight line; 2=Straight line with additional 20%; 3=Double decline balance; 4=Double decline balance with additional 20%; 5=1.5 decline balance; 6=1.5 decline balance with additional 20%; 7=Sum-of-digits; 8=Sum-of-digits with additional 20%).		
e.	Does investment qualify for investment credit (0=no; 1=yes).		
7a.	Percent of total cost (input line 4a) borrowed.	07. 100 08 07.8	________
b.	Repayment period of loan-years		
c.	Annual rate of interest on loan(%)		
8a.	Per hour[x] fuel cost of operating investment** ($)	08. 02.76 00.39	________
b.	Per hour[x] fuel cost of operating associated equipment** ($)		
9a.	Per hour[x] labor cost of operating investment & associated equipment.	09. 01.06 00.00	________
b.	Per hour[x] cost of supplies of operating investment & associated equipment.		
10a.	Repairs costs of investment: Enter estimated repairs costs over period or use in today's dollars (amount must exceed $25) OR enter type*** of machine to have model estimate repairs costs. Types of machines are: 1=tractors; 2=Self-P. Combine, Self-P. Forage harvester, Rotary Cutter; 3=Pull type combine. Pull type forage harvester, Flail harvester; 4=Self-P. swather, Self-U.L. Wagon, Side D. Rake; 5=Fertilizer equip; 6=Potato harvester, Sugar beet harvester, PTO Bailer; 7=Tillage tools, Mower; 8=Seeding equip; Boom sprayers; 9=truck; 10=Air Blast Sprayer.	10. 01816	________
11a.	Number of units* handled per hour[x]	11. 0001.00	________

* Refer to Page 1

** See instructions for Program 03, Form 3 for suggested guidelines.

*** If you cannot find your machine in the list, try to match to a machine that is similar or enter estimate of repairs costs.

x Hours are used as a measure for expressing costs in lines 8a,8b,9a,9b and as a conversion factor in line 11. You can use a different measure as long as you are consistent in these lines.

		LINE NO.	ADJUSTED ANALYSIS
Section III. Federal Tax, Rate Of Return And Cash Flow Information.			
12a.	Tax bracket in year of purchase.	12. 30|30|30	
b.	Tax bracket for first 1/2 years of investment.		
c.	Tax bracket for last 1/2 years of investment.	includes social security	
13a.	Desired percentage rate of return on investment for first 1/2 years of investment.	13. 09|09|000.0	
b.	Desired percentage rate of return on investment for last 1/2 years of investment.		
c.	Additional debt load (annual principal & interest payment in thousands of dollars) that the current business can withstand.		
Section IV. Modification Of Assumptionsxx (Enter "0" on line following last modification to be made. If none, enter "0" on line 14)			
14a.	Assumption value desired	14. 01.0|01	
b.	Assumption code		
15a.	Assumption value desired	15. 06.0|02	
b.	Assumption code		
16a.	Assumption value desired	16. 08.0|05	
b.	Assumption code		
17a.	Assumption value desired	17. 06.0|08	
b.	Assumption code		
18a.	Assumption value desired	18. 01.0|09	
b.	Assumption code		
19a.	Assumption value desired	19. 01.6|10	
b.	Assumption code		
20a.	Assumption value desired	20. 06.0|03	
b.	Assumption code		

xx See instructions for Program 03, Form 3 on how to use this section.

Program No: 03
Form No: 3
System: TOUCH-TONE PHONE

CAPITAL INVESTMENT MODEL -- INCLUDING BUY OR CUSTOM HIRE
A TELPLAN PROGRAM

NAME Natural Air ADDRESS

PHONE DATE RUN

Problem: To evaluate the investment of capital to reduce or eliminate costs including custom hire and leasing, or to generate new income.

INPUT: LINE NO. ADJUSTED ANALYSIS

Section I. Costs Reducing (Custom Hire Or Leasing) Or Income Producing Information.

		LINE NO.	ADJUSTED ANALYSIS
1a.	Cost savings (or income produced) per unit* for a certain class of expenses (or income). For example, custom rate per unit ($)	01. 015.09	
2a.	Cost savings (or income produced) per unit* for a second class of expenses (or income). For example, additional per unit annual losses associated with custom hire ($)	02. 000.89	
3a.	Normal number of units* per year on which costs will be reduced (or income generated).	03. 000378	
b.	Percent of units* indicated in Line 3a that will be absorbed by investment in the year of purchase.	100	

Section II. Investment Information.

		LINE NO.	ADJUSTED ANALYSIS
4a.	Total dollar cost including undepreciated balance of trade-in items.	04. 038974	
b.	Percentage undepreciated value of trade-in items is of total cost.	00	
5a.	If a used item enter estimated new cost of item. If new item enter same value entered in Line 4a.	05. 038974	
b.	Years plan to use the investment.	10	

* It is very important to be consistent in your units. (For example, if the custom rate is stated on acres all the other units are also to be stated in acres).

This computer program was designed by Stephen B. Harsh, Michigan State University.

	LINE NO.	ADJUSTED ANALYSIS
6a. Depreciation years b. Salvage percent c. Month of purchase (01=Jan,...., 12=Dec.). d. Depreciation type (0=Have model choose best depreciation method to use; 1=Straight line; 2=Straight line with additional 20%; 3=Double decline balance; 4=Double decline balance with additional 20%; 5=1.5 decline balance; 6=1.5 decline balance with additional 20%; 7=Sum-of-digits; 8=Sum-of-digits with additional 20%). e. Does investment qualify for investment credit (0=no; 1=yes).	06. 10 15 08 4 1	
7a. Percent of total cost (input line 4a) borrowed. b. Repayment period of loan-years c. Annual rate of interest on loan(%)	07. 100 08 07.8	
8a. Per hour^x fuel cost of operating investment** ($) b. Per hour^x fuel cost of operating associated equipment** ($)	08. 04.09 00.39	
9a. Per hour^x labor cost of operating investment & associated equipment. b. Per hour^x cost of supplies of operating investment & associated equipment.	09. 00.89 00.00	
10a. Repairs costs of investment: Enter estimated repairs costs over period or use in today's dollars (amount must exceed $25) OR enter type*** of machine to have model estimate repairs costs. Types of machines are: 1=tractors; 2=Self-P. Combine, Self-P. Forage harvester, Rotary Cutter; 3=Pull type combine. Pull type forage harvester, Flail harvester; 4=Self-P. swather, Self-U.L. Wagon, Side D. Rake; 5=Fertilizer equip; 6=Potato harvester, Sugar beet harvester, PTO Bailer; 7=Tillage tools, Mower; 8=Seeding equip; Boom sprayers; 9=truck; 10=Air Blast Sprayer.	10. 01948	
11a. Number of units* handled per hour^x	11. 0001.00	

* Refer to Page 1

** See instructions for Program 03, Form 3 for suggested guidelines.

*** If you cannot find your machine in the list, try to match to a machine that is similar or enter estimate of repairs costs.

x Hours are used as a measure for expressing costs in lines 8a,8b,9a,9b and as a conversion factor in line 11. You can use a different measure as long as you are consistent in these lines.

		LINE NO.	ADJUSTED ANALYSIS
Section III. Federal Tax, Rate Of Return And Cash Flow Information.			
12a.	Tax bracket in year of purchase.	12. 30 | 30 | 30	
b.	Tax bracket for first 1/2 years of investment.		
c.	Tax bracket for last 1/2 years of investment.	includes social security	
13a.	Desired percentage rate of return on investment for first 1/2 years of investment.	13. 09 | 09 | 000.	
b.	Desired percentage rate of return on investment for last 1/2 years of investment.		
c.	Additional debt load (annual principal & interest payment in thousands of dollars) that the current business can withstand.		

Section IV. Modification Of Assumptions[xx]
(Enter "0" on line following last modification to be made. If none, enter "0" on line 14)

14a.	Assumption value desired	14. 01.0 | 01	
b.	Assumption code		
15a.	Assumption value desired	15. 06.0 | 02	
b.	Assumption code		
16a.	Assumption value desired	16. 08.0 | 05	
b.	Assumption code		
17a.	Assumption value desired	17. 06.0 | 08	
b.	Assumption code		
18a.	Assumption value desired	18. 01.0 | 09	
b.	Assumption code		
19a.	Assumption value desired	19. 01.6 | 10	
b.	Assumption code		
20a.	Assumption value desired	20. 06.0 | 03	
b.	Assumption code		

xx See instructions for Program 03, Form 3 on how to use this section.

Program No: 03
Form No: 3
System: TOUCH-TONE PHONE

CAPITAL INVESTMENT MODEL -- INCLUDING BUY OR CUSTOM HIRE
A TELPLAN PROGRAM

NAME Low Temperature ADDRESS

PHONE DATE RUN

Problem: To evaluate the investment of capital to reduce or eliminate costs including custom hire and leasing, or to generate new income.

INPUT:	LINE NO.	ADJUSTED ANALYSIS
Section I. Costs Reducing (Custom Hire Or Leasing) Or Income Producing Information.		
1a. Cost savings (or income produced) per unit* for a certain class of expenses (or income). For example, custom rate per unit ($)	01. 016.62	
2a. Cost savings (or income produced) per unit* for a second class of expenses (or income). For example, additional per unit annual losses associated with custom hire ($)	02. -000.89	
3a. Normal number of units* per year on which costs will be reduced (or income generated).	03. 000378	
b. Percent of units* indicated in Line 3a that will be absorbed by investment in the year of purchase.	100	
Section II. Investment Information.		
4a. Total dollar cost including undepreciated balance of trade-in items.	04. 038286	
b. Percentage undepreciated value of trade-in items is of total cost.	00	
5a. If a used item enter estimated new cost of item. If new item enter same value entered in Line 4a.	05. 038286	
b. Years plan to use the investment.	10	

* It is very important to be consistent in your units. (For example, if the custom rate is stated on acres all the other units are also to be stated in acres).

This computer program was designed by Stephen B. Harsh, Michigan State University.

		LINE NO.	ADJUSTED ANALYSIS
6a.	Depreciation years	06. 10 | 14 | 08 | 4 | 1	______
b.	Salvage percent		
c.	Month of purchase (01=Jan,...., 12=Dec.).		
d.	Depreciation type (0=Have model choose best depreciation method to use; 1=Straight line; 2=Straight line with additional 20%; 3=Double decline balance; 4=Double decline balance with additional 20%; 5=1.5 decline balance; 6=1.5 decline balance with additional 20%; 7=Sum-of-digits; 8=Sum-of-digits with additional 20%).		
e.	Does investment qualify for investment credit (0=no; 1=yes).		
7a.	Percent of total cost (input line 4a) borrowed.	07. 100 | 08 | 07.8	______
b.	Repayment period of loan-years		
c.	Annual rate of interest on loan(%)		
8a.	Per hour^{x} fuel cost of operating investment** ($)	08. 05.31 | 00.39	______
b.	Per hour^{x} fuel cost of operating associated equipment** ($)		
9a.	Per hour^{x} labor cost of operating investment & associated equipment.	09. 00.89 | 00.00	______
b.	Per hour^{x} cost of supplies of operating investment & associated equipment.		
10a.	Repairs costs of investment: Enter estimated repairs costs over period or use in today's dollars (amount must exceed $25) OR enter type*** of machine to have model estimate repairs costs. Types of machines are: 1=tractors; 2=Self-P. Combine, Self-P. Forage harvester, Rotary Cutter; 3=Pull type combine. Pull type forage harvester, Flail harvester; 4=Self-P. swather, Self-U.L. Wagon, Side D. Rake; 5=Fertilizer equip; 6=Potato harvester, Sugar beet harvester, PTO Bailer; 7=Tillage tools, Mower; 8=Seeding equip; Boom sprayers; 9=truck; 10=Air Blast Sprayer.	10. 01914	______
11a.	Number of units* handled per hour^{x}	11. 0001.00	______

* Refer to Page 1

** See instructions for Program 03, Form 3 for suggested guidelines.

*** If you cannot find your machine in the list, try to match to a machine that is similar or enter estimate of repairs costs.

x Hours are used as a measure for expressing costs in lines 8a,8b,9a,9b and as a conversion factor in line 11. You can use a different measure as long as you are consistent in these lines.

	LINE NO.	ADJUSTED ANALYSIS
Section III. Federal Tax, Rate Of Return And Cash Flow Information.		
12a. Tax bracket in year of purchase. b. Tax bracket for first 1/2 years of investment. c. Tax bracket for last 1/2 years of investment.	12. 30 | 30 | 30 includes social security	
13a. Desired percentage rate of return on investment for first 1/2 years of investment. b. Desired percentage rate of return on investment for last 1/2 years of investment. c. Additional debt load (annual principal & interest payment in thousands of dollars) that the current business can withstand.	13. 09 | 09 | 000 . 0	
Section IV. Modification Of Assumptions[xx] (Enter "0" on line following last modification to be made. If none, enter "0" on line 14)		
14a. Assumption value desired b. Assumption code	14. 01 . 0 | 01	
15a. Assumption value desired b. Assumption code	15. 06 . 0 | 02	
16a. Assumption value desired b. Assumption code	16. 08 . 0 | 05	
17a. Assumption value desired b. Assumption code	17. 06 . 0 | 08	
18a. Assumption value desired b. Assumption code	18. 01 . 0 | 09	
19a. Assumption value desired b. Assumption code	19. 01 . 6 | 10	
20a. Assumption value desired b. Assumption code	20. 06 . 0 | 03	

xx See instructions for Program 03, Form 3 on how to use this section.

APPENDIX D

DRYING-TIME CALCULATION FOR THE IN-BIN COUNTERFLOW SYSTEM

```
10PRINT "Dryng time , energy consumption , drying efficiency  water removed , and dryer capacity as"

20PRINT "calculated by the drying model (CYCLE NO 5 TABLE 14) Shivvers system "
30PRINT
40PRINT "-----------------------------------------------------------------------------------------"

50PRINT "CYCLE MOISTURE CONTENT  PROPANE  ELECT.  DRYING   PROPANE*   DRYING EFF   WATER** DRYER***"

60PRINT " NO     INITIAL  FINAL      KJ     KW-h     TIME   EQUIVALENT   KJ/Kg H2O  REMOVED  CAPACITY"

70PRINT "-----------------------------------------------------------------------------------------"

80 A7=5
90INPUT "BIN DIAMETER D=;",D
100INPUT "LAYER DEPTH X1=;",X1
110INPUT "AMBIENT TEMP. DEGREE F B=;",B
120INPUT "DRYING TEMP. DEGREE F  T=;",T
130INPUT "INITIAL MOISTURE % WB  M1=;",M1
140INPUT "DESIRED FINAL MOISTURE CONTENT  M2=;",M2
150INPUT "STATIC PRESSURE  IN H2O S1=;",S1
160INPUT "WET BULB TEMPERATURE FOR DRYING AIR DEGREE F T1=;",T1
170INPUT "RELATIVE HUMIDITY OF DRYING AIR  %  U=;",U
180INPUT "DRYNG AIR  HUMID VOLUME  CUFT/LB  V1=;",V1
190INPUT "TEST WEIGTH AT INITIAL MOISTURE CONTENT  LB/BU  D6=;",D6
200 A=(#PI*D^2)/4
210L1=X1*A*D6/1.25 :REM POUNDS OF DRY CORN
220L2=L1*(100-M2)/100:REM POUNDS OF DRY MATTER
230L3=100*L2/(100-M1):REM POUNDS OF WET CORN
240W1=L3-L1 :REM POUNS OF WATER REMOVED PER CICLE


250D6=(D6)/1.25*(100-M1)/100
260E=(7.4776*U^.4584)/LOG(T):REM CALCULATION OF THE EQUILIBRIUM MOISTURE CONTENT-SILVA RELATIONSHIP
270E=E/(100-E):REM EQUILIBRIUM MOISTURE CONTENT DRY BASIS
280K6=.54*3600*EXP(-5023/(T+460)):REM CALCULATION OF THE DRYING CONSTANT
290 H=LOG(2)/K6  :REM CALCULATION OF THE TIME OF HALF RESPONSE
300 M1=M1/(100-M1):REM CHANGE MOISTURE CONTENT INTO DRY BASIS
310 M2=M2/(100-M2):REM CHANGE MOISTURE CONTENT INTO DRY BASIS
320Q=(18377.23*EXP(-.202*S1))/A :REM AIR FLOW  FOR THE 13 HP SHIVVERS DRYER
330F=A*Q :REM TOTAL AIR FLOW PER MINUTE
340 W5=(F*S1)/(6356*.6):REM CALCULATION OF THE FAN POWER
350 F=60*A*Q/V1:REM MASS FLOW RATE PER HOUR
360 D1=(X1*D6*A*1080*(M1-E))/( 24*F*H*(T-T1)): REM CALCULATION OF THE FIRST DIMENTIONLESS DEPTH UNIT
 (AT .24 FT ABOVE THE FLOOR)
370 RO=(M2-E)/(M1-E):REM MOISTURE RATIO FOR AT THE DESIRED MOISTURE CONTEN
380 Y1=LOG((2^D1-1)/(EXP(.69*D1+RO)-1))/.69:REM FIRST DIMENTIONLESS TIME UNIT
390 J1=(H/.69)*LOG((2^D1-1)/(2^(RO*D1)-1)):REM CALCULATION OF THE DRYING TIME TO DRY THE FIRST LAYER
```

```
400 D2=(D1*2):REM CALCULATION OF THE SECOND DEKPTH UNIT (AT .5 FT)
410 R1=(2^D1)/(2^D1+2^Y1-1):REM MOISTURE RATIO AT .5 FT FROM THE FLOOR
420 M3=R1*(M1-E)+E :REM MOITURE CONTENT AT .25 FT FROM THE FLOOR
430 R2=(2^D2)/(2^D2+2^Y1-1):REM MOISTURE RATIO AT .5 FT
440 M4=R2*(M1-E)+E :REM MOITURE CONTENT AT .5 FT FROM THE FLOOR
450 M5=(M3-M4)/LOG(M3/M4):REM AVERAGE MOISTURE CONTENT FOR THE SECOND LAYER
460 R3=(M2-E)/(M5-E):REM MOISTURE RATIO FOR THE SECOND LAYER
470 D3=(X1*D6*A*1080*(M5-E))/(.24*F*H*(T-T1)):REM DIMENTIONLESS DEPTH UNIT FOR THE SECOND LAYER AFTE
R THE FIRST HAD BEEN DROPPED
480 Y2=LOG((2^D3-1)/(EXP(.69*D3*R3)-1))/.69:REM DIMENTIONLESS TIME UNIT FOR THE SECOND LAYER AFTER T
HE FIRST HAD BEEN DROPPED
490 J2=Y2*H :REM CYCLING TIME OR TIME REQUIRED TO DRY  THE SECOOND LAYER AFTER THE SECOND HAD BEEN D
RIED
500J2=J2*60:REM CYCLING TIME IN MINUTES
510J1=J1*60:REM TIME TO DRY THE FIRST LAYER IN MINUTES
520E6=((F/60.0)*J2*.248*(T-B))/(.7*W1):REM CALCULATED DRYING EFFICIENCY
530B1=(60*A*X1)/(J2*1.25):REM DRYER CAPACITY BUSHEL PER HOUR
540E9=((W5*.7457)/(A*X1/1.25))*(J2/60)*6.2/.9 :REM ELECT. COST AT 6.2 CENTS PER KILOWATT
550C0=(((W1*E6)/92000)*45.7)/(A*X1/1.25) :REM PROPANE COST (CENTS PER BUSHEL)
560 C2=(C0*X1*A/(1.25*45.7))/(J2/60)*92000 :REM  TOTAL BTU FROM PROPANE PER HOUR
570P8=((E9*50/6.2)/(J2/60)) :REM ELECTRICITY COST PER 50 BUSHELS OR PER CYCLE
580P1=(C2+(P8*3413))/92000:REM PROPANE EQUIVALENT PER HOUR
590W1=W1*60/J2:REM LB OF WATER REMOVED PER HOUR
600M1=(M1/(1+M1))*100
610M2=(M2/(1+M2))*100
620C2=C2*1.055
630P1=P1*3.785
640E6=E6*2.333
650W1=W1*.4536
660B1=B1*.025
670PRINTUSING 690,A7,M1,M2,C2,P8,J2,P1,E6,W1,B1
680PRINT J1,"TIME TO DRY THE FIRST LAYER"
690% ##     ##.##  ##.##   #######  ##.#     ###.#     ##.#          ####       ####      ###.#
700PRINT "---------------------------------------------------------------------------------------------"
```

Dryng time , energy consumption , drying efficiency water removed , and dryer capacity as calculated by the drying model (CYCLE NO 5 TABLE 1*) Shivvers system

CYCLE NO	MOISTURE CONTENT INITIAL	FINAL	PROPANE KJ	ELECT. KW-h	DRYING TIME	PROPANE* EQUIVALENT	DRYING EFF. KJ/Kg H2O	WATER** REMOVED	DRYER*** CAPACITY
5	25.00	18.60	1566008	6.4	18.6	61.9	4745	331	4.0

53 44072874335 TIME TO DRY THE FIRST LAYER

THE ABOVE RESULTS ARE FOR :
BIN DIAMETER D=; 18
AMBIENT TEMP. DEGREE F B; 53.4
DRYING TEMP. DEGREE F T=; 160.5
INITIAL MOISTURE % WB M1=; 25
DESIRED FINAL MOISTURE CONTENT M2=; 18.6
STATIC PRESSURE IN H2O S1=; 2.9
WET BULB TEMP. FOR THE DRYING AIR , DEGREE F T1=; 85
RELATIVE HUMIDITY OF THE DRYING AIR % U=; 4.5
DRYING AIR HUMID VOLUME CUFT/LB V1=; 15.69
TEST WEIGHT AT INITIAL MOISTURE LB/BU D6=; 31.8

* Liters per hour.
** Kilos per hour.
*** Tons per hour.