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A COMPARISON OF LOW-TEMPERATURE STIRRED IN-BIN DRYING WITH IN-BIN NATURAL AIR DRYING OF SHELLED CORN

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A COMPARISON OF LOW-TEMPERATURE STIRRED IN-BIN DRYING WITH IN-BIN NATURAL AIR DRYING OF SHELLED CORN

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ABSTRACT

A COMPARISON OF LOW-TEMPERATURE
STIRRED IN-BIN DRYING WITH IN-BIN
NATURAL AIR DRYING OF SHELLED CORN

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Low-temperature in-bin grain drying with supplemental heat results in overdrying at the bottom and underdrying at the top of the bin. To reduce this effect, stirring devices have been introduced. The objective of this thesis is to compare the performance characteristics of a low-temperature stir-drying and natural air drying systems.

The field tests were conducted at Kalchik Farms, Bellaire, Michigan in the fall of 1979 and 1980. The corn was dried to 22-23% moisture in a high temperature dryer before drying to 15-16% in the low-temperature and natural air drying phases. The grain quality and the drying costs were analyzed and compared.

The results indicate that low-temperature stir-drying requires slightly less energy than natural air drying, is a more reliable system, and results in better quality corn. The total drying cost for the stirred low-temperature drying was \$1.45/ton per percentage point moisture removal, compared with \$1.88/ton-point for the natural air system.

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a	constant
A	area, m^2
C	constant
C	mass concentration coefficient, kg/m^3
C	specific heat, kJ/kg-°C
CMM	air flow rate, m^3/min
D	diffusion coefficient, cm^2/sec
DEL	moisture content by delGuidice thin-layer equation, decimal d.b.
DELT	time increment, hr
DEPTH	total bed depth, m
DFK	drying parameter, 1/hr
DMISRA	dry matter loss by Misra thin-layer equations, percent
DMS	dry matter loss by Sabbah and delGuidice thin-layer equations, percent
DRUG	dry matter loss by Rugumayo thin-layer equations, percent
EXMC	experimental corn moisture content, decimal d.b.
F	mass transfer rate, kg/cm^2 sec
g	acceleration due to gravity, m/sec^2
G	dry weight, kg/m
G	mass flow rate per unit area, $kg/h\text{-}m^2$
g_c	gravitational acceleration 9.8 m/sec^2
h_c	convective heat transfer coefficient, $w/(m^2\text{-}°C)$

h_{fg}	latent heat of vaporazation of water in a product, kJ/kg
h_{xy}	convective coefficient, $w/(m^2\text{-}°C)$
H	absolute humidity of air, kg/kg
HIN	inlet air absolute humidity, kg/kg
HR	time, hr
i	internal energy, kJ/kg
INDPR	number of nodes between prints
k	parameter, 1/hr
k	thermal conductivity, w/m-°C
K	coupling coefficient
K	phenomenological coefficient
K	thickness, m
K	subscript or superscript
K	extinction coefficient, 1/m
L	length, m
LT-NS	low temperature (electric heat) non-stir in-bin drying
LT-ST	low temperature (electric heat) stir in-bin drying
m	constant
M	moisture content, decimal, d.b.
MISRA	moisture content by Misra thin-layer equations, decimal d.b.
MPM	meters per minute
MR	moisture ratio, decimal
NA	natural air in-bin drying
NEQ	equation type
NLPF	number of layers per meter
p	pressure, N/m^2
PS	saturated vapor pressure, Pa

PSDB	vapor press, Pa
q	heat energy, w/m^2
q	heat flow rate $kJ/h\text{-}m^2$
Q	heat flow rate kJ/hr
r	radius, m
rh	air relative humidity, decimal
R	radius, m
RH	air relative humidity, decimal
RUG	moisture content by Rugumayo thin-layer equations, decimal d.b.
SAB	moisture content by Sabbah equation, decimal, d.b.
SMC	moisture content by Sabbah and delGuidice equations, decimal d.b.
t	time, hr
t	thickness, m
t	temperature, °C
t_a	ambient air temperature, °C
t_b	bulk temperature, °C
t_m	mixed mean fluid temperature, °C
t_p	plate temperature, °C
T	air temperature, °C
TA	ambient air temperature, °K
TAIR	drying or rewetting air temperature, °K
TBTPR	time between output, hr
TEQ	equivalent reference storage time, hr
TGRN	grain temperature, °K
THIN	inlet or initial grain temperature, °C
TIN	inlet or initial air temperature, °C

TT	total time, hr
U	heat loss coefficient, w/(m^2-°C)
U	fully developed fluid flow rate, m/hr
W	weight, kg
W	width, m
x	distance, m
x	x-coordinate
XME	equilibrium moisture content, decimal, d.b.
XMO	inlet or initial moisture content, decimal d.b.
y	y-coordinate
y	distance, m

LIST OF SYMBOLS USED AS SUBSCRIPTS

a	air
d	downward
D	diameter
e	equilibrium
H	storage array for humidity ratios - kg-H_2O/kg dry air
H	heat
i	inlet
L	long
L	loss
o	initial
o	outlet
p	product
s	surface
t	time
T	air temperature array
T	total
u	useful
up	upward
v	vapor
w	water

Greek Symbols

α	constant
∂	finite difference
δ	constant
Δ	difference
Θ	grain temperature, °C or °K
μ	dynamic viscosity, kg/(m-hr)
ρ	density, kg/m^3
σ	constant variance of observation errors
σ	Stefan-Boltzman constant, $5.67x10^{-8}$ $w/(m^2 - °K^4)$
τ	shear stress, N/m^2
ν	kinematic viscosity, m^2/hr
$\underline{\phi}$	diagonal matrix

1. INTRODUCTION

The United States is the leading corn producer in the world. In 1978 the U.S. produced nearly 50% of the total world corn production (FAO, 1979). In 1979 the U.S. produced 198 mega metric tons of corn for grain (USDA 1980).

The energy consumption on American farms is low compared to other sectors. According to Friedrich (1978) energy use in the United States is as follows:

On farm food production	3-4%
Entire food production	12-17%
Industrial processes	37%
Transportation	26%
Others	20-25%

Thus, compared with energy use in industrial processes and transportation, energy consumption in agriculture is indeed small. However, considering the annual total agricultural energy consumption of 2.65×10^9 mJ (2.5 quadrillion BTU's) energy conservation in agricultural production will result in considerable overal energy savings (Friedrich, 1978).

In its 1976 annual report to the Congress, the U.S. Energy Research and Development Administration (ERDA) pointed to the following facts (Friedrich, 1978):

1. A barrel of oil saved can result in reduced oil imports.
2. It costs less to save a barrel of oil than to produce one through the development of new technology.
3. Energy conservation is beneficial to the environment in comparison to energy produced and used.

4. Capital requirements to increase the energy efficiency are generally lower than the capital needs to produce an equivalent amount of energy from new sources since most new supply technologies are highly capital intensity.
5. Conservation technologies can generally be implemented at a faster rate and with less government involvement in the near term than can new supply technologies.
6. Energy efficiency actions can reduce the pressure of accelerated introduction of new supply technologies. Since the actions persist over time the benefits are continuing.

With an abundant energy supply at reasonable costs, it is still profitable for one U.S. farmer to produce enough food for more than 50 other individuals (CAST, 1977). However, with the continuing fossil fuel supply limitations, rapidly increasing costs and lack of price projections, the profit margin in agricultural production is continuously decreasing. It is therefore, important to consider ways and means of improving production techniques and increasing the energy efficiency on American farms. The Council for Agricultural Science and Technology (CAST, 1977) suggested the following with regard to farm operations:

- reduce energy use for fertilizer application and tillage;
- substitute enterprises that consume less energy;
- invest in alternate technologies that substitute energy inputs and reduce energy use;
- invest in alternative energy sources such as solar, wind and biomass;
- modify farm enterprises to make them more efficient for the natural environmental conditions; and
- cease farming if the adjustments are too difficult.

Artificial corn drying is an energy intensive system. About 60% of the energy required to produce corn on the farm is used for artificial drying (Ag Engr. Dept. MSU, 1974). Inspite of the high energy demand for drying, over 80% of the corn produced in the U.S.A. is artificially dried (ASAE 1978). Artificial drying has the following advantages (Brooker et al., 1974):

- artificial drying allows early harvesting which in turn reduces storm and shattering field losses and permits early land preparation for the next crop;
- planning the harvest season to make better use of labor, because harvesting is independent of grain moisture content fluctuations in the field;
- long time storage without deterioration;
- enables farmers to take advantage of higher price a few months after harvest;
- maintenance of grain viability;
- maintains grain quality; and
- allows the use of full season hybrids (longer maturing varieties) that yield more grain per hectare.

Considering the above advantages it is obvious that energy intensive corn drying cannot be avoided without undue loss of corn quantity and quality at the farm level.

The current artificial grain dryers use convection type heaters that burn fossil fuel, usually liquefied petroleum (LP) gas or natural gas. According to Friedrich (1978), high temperature dryers operate at about 50 percent efficiency in utilizing fuel to evaporate the moisture in grains. It takes about 4650 to 8140 kJ of heat to remove one kilogram of water from corn depending on the initial and final moisture content, the amount of fines in the grain, and weather conditions (Brooker,et al.,1978). It is obvious that the current high temperature grain dryers use too much fuel. There is room for improvement and design of alternative grain drying systems is necessary to reduce energy used for grain drying.

ASAE (1978) listed four possibilities of reducing fossil fuel requirements for grain drying:

1. increased use of high moisture corn storage used to feed animals on or nearby farms where corn is grown;
2. combination systems using the advantage of high speed, high temperature dryers coupled with energy savings of in-stoarge, low temperature or natural air drying.
3. solar heated drying systems; and
4. incineration of crop residues used as a crop drying energy source.

Energy savings of up to 50 percent using different combination drying systems have been reported by Bakker-Arkema et al. (1978, 1979 and 1980), Kalchik et al. (1979), and Silva (1980).

1.1 Michigan Corn Production and Energy Use

According to the USDA (1980), Michigan ranked ninth in the United States in 1977 and 1978 and eighth in 1979 in the production of grain for corn. Michigan corn accounted for 3.1% of the total United States production in 1977, 2.7% in 1978 and 3.1% in 1979. The shelled corn production in Michigan increased from 2.3 million tons in 1960 to 3.9 million tons in 1975 (Fedewa et al., 1979). During the same period, the energy used for drying increased from 75.2 x 10^{10} kJ to 329.5 x 10^{10} kJ (Brooker, 1977). According to the USDA (1980) the Michigan corn production in 1979 was just over 6.03 million tons. Information on corn drying energy for 1979 is not yet available. If the same trend continues, the energy for drying corn in 1979 was likely to be over 400 x 10^{10} kJ. The increase in energy consumption is largely due to the shift from ear-corn to a shelled corn harvesting systems, and also due to the net increase in corn production.

As previously stated, more than 60% of the energy required to produce corn on the farm is used for artificial drying in 1977, 74.9% of the Michigan corn was artificially dried in some kind of heated air drying system; over 88 percent of fuel was propane (Fedewa et al., 1978).

1.2 Corn Drying in Michigan

Heated air drying of shelled corn is a common practice in Michigan due to the characteristic weather conditions. According to Fedewa et al. (1975 and 1978), corn drying practices are as shown in Tables 1, 2 and 3.

It has been estimated that at least 60% of the 6.03 million ton Michigan corn crop was artificially dried in 1978 (Bakker-Arkema et al., 1979), primarily in automatic batch dryers between 80° and 110°C, and in-bin batch type drying systems between 43° and 60°C. About 142 kg of water per ton is removed from corn harvested at 26% moisture content and dried to 15.5%. Assuming an average energy efficiency of 7000 kJ/kg of water in conventional on-farm high temperature drying systems, approximately 6 x 10^{12} kJ or 24.6 x 10^7 liters of liquid propane were required to dry the 1979 Michigan corn crop; this is equivalent to $30,061,500 at 1979 prices (11.9¢ per liter of propane).

1.3 Corn Production and Drying Problems in Kenya

Cereal grains, in particular corn (white maize), and legumes constitute the stable food for most Africans, including the Kenyans. Cereals are grown by "small scale" (1-10 hectares) and "large scale" farmers (over 10

Table 1. Drying of corn stored on farms, by selected states.

State	Dried Naturally in field or in storage				Dried artificially			
	1974	1975	1976	1977	1974	1975	1976	1977
	Percent							
Michigan	40.2	45.3	-	25.1	59.8	54.7	-	74.9
Illinois	21.0	33.5	13.0	-	79.0	66.5	87.0	-
Indiana	12.0	12.2	11.8	10.7	88.0	87.8	88.2	89.3
Iowa	37.5	30.6	29.3	29.3	62.5	69.4	70.7	70.7
Wisconsin	39.7	45.3	44.8	-	60.3	54.7	55.2	-

Source: Fedewa et al., 1978.

Table 2. Percentage of corn stored on farms in Michigan by size group.

Harvested size Group - acres	Dried naturally in field or storage		Dried artificially	
	1975	1977	1975	1977
1 - 49	90.5	88.8	9.5	11.2
50 - 149	62.1	45.7	37.9	54.3
150 - 249	36.5	17.4	63.5	82.6
250 - Over	6.1	7.4	93.9	92.6
All Farms	45.3	25.1	54.7	74.9

Source: Fedewa et al., 1978.

Table 3. Percentage of shelled corn dried artificially on farms in Michigan in 1974, 1975 and 1977.

Dryer Type	1974	1975	1977
Batch	28.1	37.2	40.0
Batch-in-bin	20.2	10.9	10.7
Continuous Flow	45.7	10.9	40.4
In-storage Layer	14.3	9.2	8.4
Other Dryers	1.7	3.2	0.5

Source: Fedewa et al., 1978.

ha) under different ecological and socio-economic, environmental and technological conditions. Thus, the production problems are many and varied.

Large scale farmers produce corn almost entirely as a cash crop and usually have the equipment and the know-how to handle the crop more efficiently than the small scale farmers. The latter depending on how "small" they are, produce corn for home consumption and for cash if they have a surplus. Some maize is consumed fresh before it matures and the rest is stored for seed and future consumption. Small scale farmers face major problems in drying, cleaning and storage of corn and other grains.

Handling practices vary from place to place within Kenya. Some farmers, especially the subsistent farmers, harvest unhusked corn and suspend it from trees, on poles, over fires in their homes or on special platforms. Others have traditional granaries in which dehusked or unhusked corn is kept for natural drying. The granaries vary in size, accessability for inspection and removal, and the degree of protection against insects, rodents and the weather. Some maize may be sun-dried (either as ear-corn or shelled grain) by spreading it on mats, ground or flat rocks.

Solar-drying at the homestead is economical, but is risky due to uncertainties about the weather, and labor availability for handling. Therefore, most farmers leave the crop to dry naturally in the field, and harvest when it is sufficiently dry (16 to 18%) for solar drying. This leads to field infestation by insects, birds, and molds. Also, the land preparation for the next crop is delayed. To avoid this delay, some farmers cut the corn stalks and stack them in 2 to 4 meter diameter conical stacks in the field. The stacks are left in the field for up to two months to dry.

The long term storage of corn is undertaken by the Kenya Cereals

Board (a Government agency). The board is charged with drying and storage of cereals for the purpose of price stabilization and for emergency needs (such as occur during a drought). The Board handles 20% of the total Kenyan corn production. The remainder is handled by individual farmers or co-operatives.

The Board buys maize from farmers at a specified quality standard and government set price. Maize that is above 13% moisture content (wet basis), or insect damaged, or contains specified foreign materials, broken or colored kernels, is not acceptable to the Board.

For long term strategic storage (up to 3 years), the Board uses Cyprus bins. Maize is artificially dried to 12% moisture for long term storage. For short term storage maize at 13% moisture is stored in masonry sheds in 90 kg bags.

The Board handles about 500 thousand metric tons annually. According to FAO (1979), the total Kenyan maize (corn) production was 2.6 million tons in 1976; 2.553 million in 1977 and 2.35 million tons in 1978. The annual loss due to insects alone has been estimated at between 5 and 7%. This amounts to a monetary loss of approximately $16 million annually (Anderson and Pfost, 1978).

Grain storage problems differ in various regions of Kenya. Insect damage is by far the most severe problem. Drying problems are more severe in the surplus producing areas with higher rainfall than in the drier grain-deficient areas. Long-term storage conditions are most favorable at higher altitudes due to lower temperatures and lower relative humidities than in the lower altitudes.

Judging from the available literature on grain drying and storage in Kenya, it appears obvious that storage problems are more severe than drying problems. However, storage and drying are closely related. Since the most severe insect infestation, plus molding and rotting occurs in the field while natural drying takes place, it is reasonable to postulate that artificial drying can contribute substantially in minimizing the storage problem. It has been observed that insect infestation in the field does not start at high ear moisture contents. Although the exact moisture content at which this occurs has not been documented. It largely depends on the insect species. If the corn can be harvested before infestation, dried quickly before molding and then stored in a well maintained structure (with regular insecticide application), grain can be stored on the farms much longer than appears currently possible.

As stated earlier, most Kenyan corn producers are small scale farmers. As in Michigan (see Table 2) most small farmers dry their crop naturally, either in the field or in some type of a crib. Kenya has no oil nor metalic minerals and has a foreign exchange shortage. It is therefore, necessary to design grain drying systems that are effective, cheap, least energy (fossil fuel) consumptive and made of locally available materials.

In the past the emphasis on grain storage problems in Kenya has been largely entomological. There has been little research effort on grain drying and storage structures; due to a shortage of agricultural engineers in the country. After their study on smallholder grain storage problems in Kenya Anderson and Pfost (1978) recommended that a thorough study should be conducted on grain storage needs in Kenya. They also recommended that personnel be trained in seed science and grain drying and handling technology to alleviate the severe shortage of local personnel qualified to solve the grain drying/storage problems.

The research discussed in this thesis is a part of an effort to study the feasibility of natural air and combination drying systems in Michigan.

The knowledge gained will be used to modify these systems (if necessary) to suit Kenyan conditions.

1.4 Objectives

The overal objective of this study is to compare the performance characteristics of in-bin shelled corn stir-drying with that of in-bin natural air drying. As a part of the combination drying systems, a continuous high temperature crossflow dryer (Kan-Sun model 8-15-10) is used to dry corn from about 33 to 22-23 percent (wet basis), to prepare the corn for in-bin low temperature stir-drying and natural air drying.

The specific objectives are:

- to model stir-drying
- to study the effect of stir-drying on:
  - a. the grain quality and its uniformity
  - b. the moisture content uniformity of the grain in the bin
  - c. the drying time, and
  - d. the energy consumption and the drying cost
- to demonstrate the technical and economic feasibility of in-bin stir-drying in high temperature/low-temperature combination drying.

2. LITERATURE REVIEW

In this study high temperature, high speed drying was combined with low-temperature stir drying. These drying processes affect grain quality in different ways. It is well known that grain and seeds are exceedingly durable but highly perishable if poorly handled. If well harvested, and stored at low moisture content and low temperature grains will retain the original germinability and other desirable qualities for a long period of time. The following literature review was developed to study the need for grain drying, the effect of various drying methods on grain quality, and the development of stirring devices for in-bin deep bed drying.

2.1 Importance of Grain Drying

The importance of grain drying has been discussed by Brooker et al., (1974). Drying facilitates early harvest, thus reducing field losses from storm, insect damage and natural shattering. Field conditions are often better for harvesting early in the season. Early harvest permits early and timely seedbed preparation for the next crop. (This is particularly important in some tropical areas where two or more crops can be raised in one year).

Grain drying permits farmers to plan the harvest season to make better use of labor and machinery since harvesting is not dependent on fluctuations of the moisture content of the grain in the field. Finally, the early harvest enables farmers to take advantage of higher prices early in the harvest season.

The most important advantage of grain drying is that it permits long-time storage without deterioration in quality. By removing excess moisture from the grain the possibility of natural heating of the grain due to respiration is reduced. Thus grain viability is maintained during storage. Dried grain (at moisture content below 13%) is less prone to insect, mites and fungi damage than wet grain.

2.2 Corn Quality as Affected by Drying Methods

The desirable corn properties are dependent upon the intended use of the corn. In the U.S.A. corn is mainly used as animal feed, with smaller useage as a human food source, seed and industrial starch manufacture. Corn quality is dependent upon several factors: (1) the variety characteristics, (2) the environmental conditions during growth, (3) the time and the harvesting procedure, (4) the drying method, and (5) the storage practice (Brooker et al., 1974). During the drying process corn quality is affected by the grain temperature and the drying rate.

Corn in the U.S.A. is officially graded for quality under the Grain Standards Act. The grades and grade requirements are listed in Table 4. As can be seen from the table, the standard for corn only considers test weight, moisture content, broken and damaged corn, and foreign materials. There are other properties which are of importance to specific corn users that are excluded from the standard: such as millability, viability and susceptibility to breakage.

2.2.1 Effect of Drying on Nutritional Feed Value

The most important quality factor of corn for animal feed is the nutritional value. The effect of drying temperature on the nutritional value of corn for animal feed has received considerable research attention. Hathaway et al. (1952) found that drying corn at temperatures above 60°C

Table 4. Numerical grades and sample grade requirements for yellow, white and mixed corn.

Grade	Minimum test weight per bushel lb	Maximum Limits			
		Moisture %	BCFM %	Damaged kernels	
				Heat damaged %	Total
1	56	14.0	2.0	0.1	3.0
2	54	15.5	3.0	0.2	5.0
3	52	17.5	4.0	0.5	7.0
4	49	20.0	5.0	1.0	10.0
5	46	23.0	7.0	3.0	15.0

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

Source: Brooker et al.(1974)

significantly decreased its energy content and palatability. Sullivan et al. (1975) reported that heat has a definite effect on the nutritional value of corn; also, that the decrease in commercial quality due to drying at high temperatures may not result in a decreased value of corn as animal feed.

Jensen et al. (1960) reported that drying temperatures of 60°C, 82.2°C and 104°C have no deleterious effect 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 nicotinic acid, pantothenic acid, pyridoxine, and riboflavin content of corn dried at 43.3°C, 48.8°C and 82.2°C.

Recently, Jensen (1978) showed that roasting corn at 14% and 23% moisture at 27°C and 150°C reduced the availability of lysine. He found that niacin is unaffected by roasting temperature, but pyridoxine (vitamin B6) availability is significantly reduced in 14% moisture corn when it is dried at 160°C.

From the above review it appears that corn drying at temperatures above 60°C results in some minor nutritional changes. However, nutritionists do not agree on the effects of drying temperature on the feed value of corn (Brooker et al., 1974). It is generally recognized that physical and chemical properties such as consistency, energy content, palatability, hardness, color, moisture, vitamins, protein and amino acid profile are affected by drying temperature (Williamson, 1975).

2.2.2 Effect of Drying on Corn Milling Quality

Farmers and elevator operators who dry corn often consider only its feed value. Corn millers are concerned about the increasing volume of artificially dried corn coming into the market (Freeman, 1978; Rutledge, 1978).

High starch yield (millability), maximum yield of selected fractions and prime product mix, and low fat content are the most important desirable characteristics of corn for milling. Brekke et al. (1973) compared corn dry-milling response to in-bin natural air drying with artificial drying in a small experimental fluidized dryer drying at air temperatures from 32 to 143°C (maximum corn temperatures were 32 to 104°C respectively). They found that the yield of total grits recovered by sieving, aspiration and flotation decreased with increasing drying air temperatures. The fat content of the grits increased with increasing air temperatures. Prime products recovered by rolling and grading followed similar patterns; however, sometimes yields and fat contents were less satisfactory. The results also showed that the cold paste viscosity of selected products increased as corn was dried at elevated temperatures. The corn dried with natural air had the best dry-milling quality. Drying at 60°C yielded corn of acceptable dry-milling quality except for a high percentage of stress cracks.

Freeman (1973) discussed the quality factors affecting the value of corn for wet milling. He indicated that drying at high temperatures causes "case hardening" of proteins. Case-hardened protein affects the millability by impairing separation and purification of starch. The result is starch with a high protein content and reduced viscosity. The drying temperature, drying rate and the initial corn moisture content determine the degree of case hardening. Freeman suggested that high moisture corn for wet milling should be mildly dried at low temperature (up to 5% moisture reduction) before drying in high temperature dryers. High drying temperatures may also destroy some amino acids especially lysine.

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.

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

2.2.3 Drying Corn for Seed

Generally the techniques used to dry seeds do not differ greatly from those used to dry grain for other purposes. However, extra dryer control and management must be taken in order to ensure a high degree of germination (Copeland, 1976). The drying air temperature, the drying rate and the initial moisture content are the most critical factors affecting the germinating quality. Copeland (1976) stated that the higher drying temperature limit varies with the type of seed, but should not exceed 38°C. The highest safe temperature also depends on the initial moisture content. Ulileman and Ullstrup (cited in Hukill, 1954) showed that seed corn can be dried safely at 49°C if the moisture content is less than 25%; for moisture above 25%, 38°C is the upper limit.

An excessive drying rate may cause stress cracks. Over dried seeds are susceptible to mechanical damage, which is detrimental to seed quality (Copeland, 1976).

2.2.4 The Effect of Drying on Corn Commercial Grade

The effects of artificial corn drying on its composition, nutritional value, viability as seed, and industrial processing have been discussed in the previous sections of the literature review. The above factors are not included in the determination of commercial grade. As shown in Table 4 the only factors considered in the grain standard code for corn are: (1) the test weight, (2) the moisture content, (3) the broken corn and damaged corn, and (4) the presence of foreign materials. Artificial drying has a direct effect on the test weight, the moisture content and on the percentage of heat damaged corn, and has an indirect effect on broken corn. These factors will be reviewed in the following section.

2.2.4.1 Test Weight

The corn test weight is the true density and is influenced by grain shape, grain surface texture, moisture content, type and amount of impurities, size and uniformity, temperature, and other factors that affect the packing characteristics. According to Freeman (1973), test weight may indirectly indicate the wet milling quality of corn. High temperature drying may cause case hardening of proteins and reduce the extent of kernel shrinkage resulting from moisture removal and hence low test weight. Protein damage affects millability by inhibiting separation and purification of the starch.

Hall (1972) studied the effect of drying temperature on test weight of shelled corn. According to his observations, the test weight increases significantly during drying. The increase is due to shrinkage with loss of moisture and decrease of the coefficient of friction on the surface, thus permitting closer packing of the kernels. The test weight increase is less at higher drying temperatures, possibly due to case hardening. Hall observed that the test weight reaches a maximum and declines with further drying. The maximum test weight is reached at 14 to 16% moisture (Brooker et al., 1974).

The amount of test weight increase with drying depends upon: (1) the degree of kernel damage, (2) the initial moisture content, (3) the temperature reached by the grain during the drying process, (4) the final moisture content, and (5) the grain variety. Early harvested, high moisture grain is not exposed to much weathering and shows a higher test weight after drying than the same grain harvested later at a lower moisture content (Brooker,et al.,1974).

A higher test weight corn is a better quality grain and offers some saving in storage since less storage volume is required to store the same amount of dry matter.

2.2.4.2 Stress Cracks and Broken Corn

Although 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. The drying and cooling processes directly affect the degree of stress cracking and thus determine the susceptibility of corn to breakage during subsequent handling.

Thompson and Foster (1963) defined stress cracks as the fissures in the endosperm, or starch inside the kernel, in which the seed coat is not ruptured. Their results which related the drying rate and the amount of expected breakage have been confirmed by various authors. Ross and White (1972) studied the effect of overdrying on stress cracking in white corn. Their results show a general decrease in stress cracking as the white corn dried to lower moisture content, and as drying started at lower moisture contents. These phenomena are difficult to explain. However, there may be some physical and chemical changes during over-drying which make the grain kernel more resistant to cracking during the cooling period. Generally, stress cracking decreases with decreasing drying air temperature. Slow cooling of both the white and yellow corn after drying results in a dramatic reduction in the number of checked kernels, particularly at drying air temperatures above 71°C (160°F).

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

Freeman (1973) indicated that broken kernels too large to be removed by screening for wet milling may release starch granules during steeping. Free starch in the steeping water causes fouling of evaporator surfaces during steep water concentration.

2.2.4.3 Other Corn Quality Characteristics Affected by Artificial Drying

In addition to the factors discussed in previous section, artificial drying affects other grain characteristics such as color and taste. Ross and White (1972) concluded that darkening and yellowing of white corn was apparent when it was dried with air at 88°C and 104°C to lower moisture content., and for those started at higher moisture content. Discoloration was only slight for samples dried at 71°C and those started at 25% moisture content dried at 104°C to 14% final moisture. High drying air temperatures and high drying rates are detrimental to grain quality, whatever the intended use of the grain. Low-temperature and natural air drying, if properly managed, may result in better quality grain and reduced drying costs.

2.3 Drying Systems

There are three basic methods of grain drying: high and low-temperature methods, and combination drying. In the U.S.A., high temperature drying has been the primary technique for more than 25 years. This method is fast, but has a very low energy efficiency, a high fossil-fuel consumption, and usually results in a low grain quality. Low-temperature grain drying (energy for the low heat may be obtained from electricity, liquid propane, solar energy, or any other heat source) is an energy efficient process and usually results in high quality grain, if properly managed. Mold spoilage risk is the main problem encountered in warm and humid areas. Natural drying is a low temperature drying method and takes place when grain is either left standing (or stacked) in the field to dry, or harvested and kept in a crib to dry. The latter method is practiced in the third world tropics and is the most risky since it exposes grain to the weather, insects, rodents, birds, deseases and other destructive elements.

Combination drying processes for drying shelled corn started in the late 1970's (Brooker et al., 1978). In these processes high speed batch or continuous flow drying is combined with low heat or natural air in-bin drying. The high speed, high temperature dryers dry the corn to a moisture range of 18-23%. The corn is then transferred to storage where it is slowly dried to a safe storage moisture content. Combination drying offers a number of advantages, including:

1. increased throughput
2. increased fuel efficiency, and
3. improved product quality (compared to corn dried by high speed, high temperature processes.

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

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

flow systems are combined with low heat in-bin drying systems.

For the research reported in this thesis items (1) and (4) have been combined. These two grain drying techniques will now be reviewed in detail.

2.3.1 Column Batch Dryers

Column batch dryers are stationary bed dryers, in which the air moves across a stationary grain column (see Figure 1). The dryer is often portable so that it can be moved from location to location when not filled with grain. According to Brooker et al. (1974) column batch dryers have the following characteristics:

1. column thickness is usually from 30.5 cm to 45.7 cm;
2. column batch dryers operate at high air flow rates (1.42 m^3/min to 2.83 m^3/min);
3. drying air temperatures vary from 82°C to 116°C;
4. due to the high air flow rate coupled with a narrow column, the moisture gradient across the column is less than with batch in-bin systems; and
5. drying is completed in a 1 to 3 hr period depending on the initial grain moisture content, and the need for cooling.

Column dryers are particularly popular because of their simple construction and operation, and because their initial cost is generally lower than that of continuous flow types (Sutherland, 1975). They are suitable for moderate grain volumes (250 to 650 tons annually) with high initial moisture content. Because the dryer has no storage function, it requires well planned and coordinated handling and storage systems (Brooker et al., 1978).

The fuel consumption and therefore, the operating costs depend on the moisture removal range. The fuel efficiency decreases with decreasing

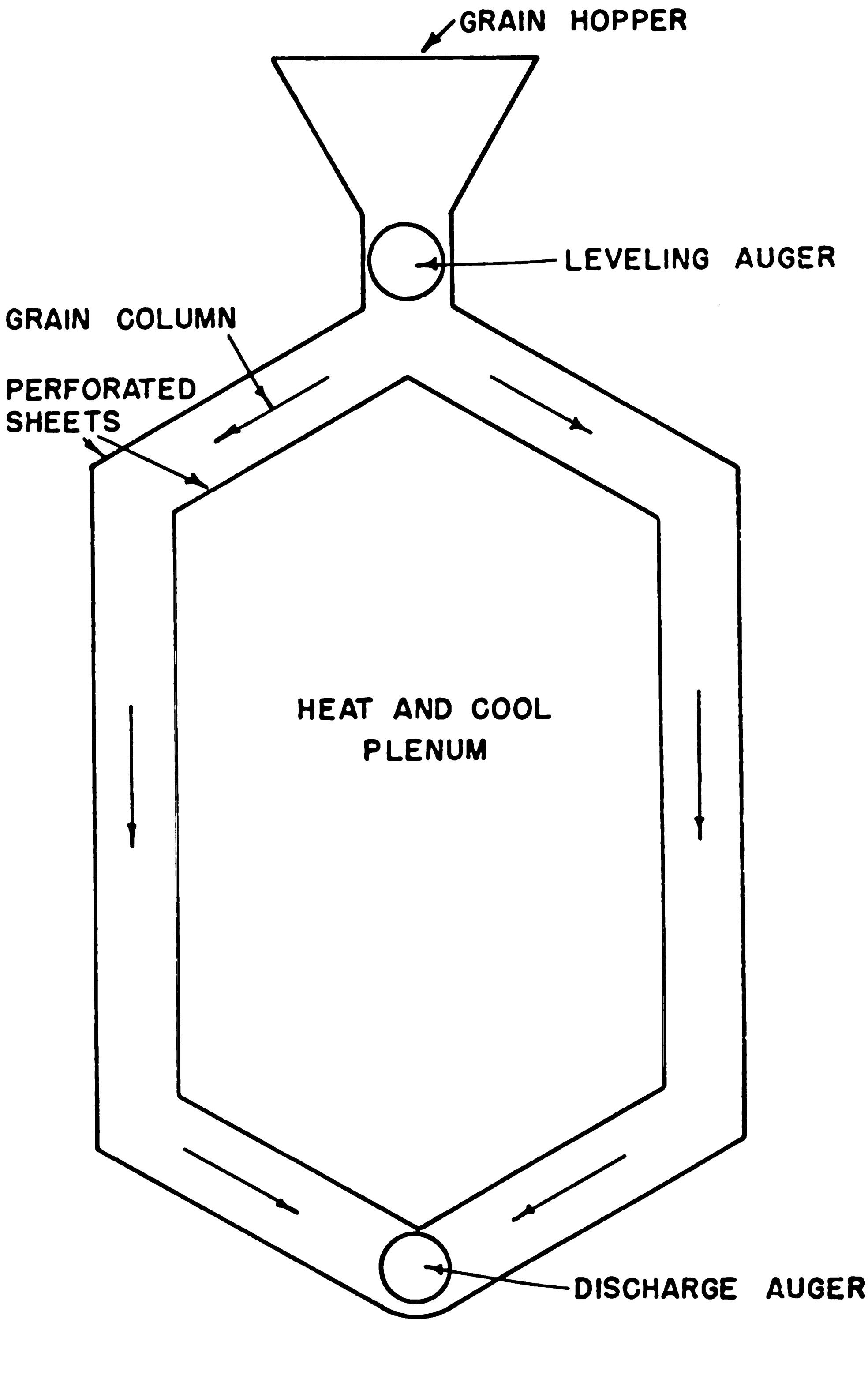


Figure 1. Batch Column Dryer.

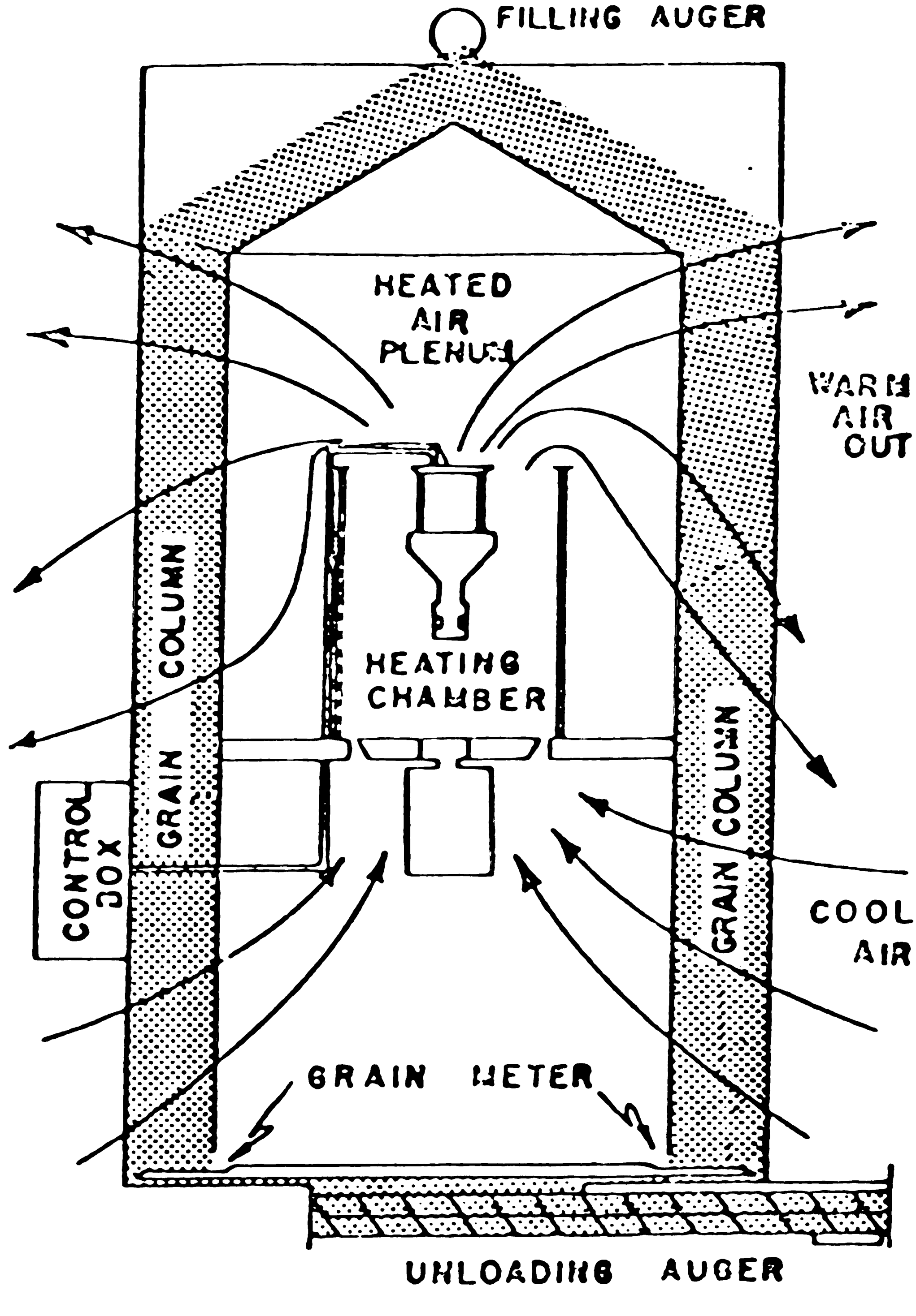


Figure 2. Crossflow dryer with forced air drying and reversedflow cooling (from Brooker et al., 1974).

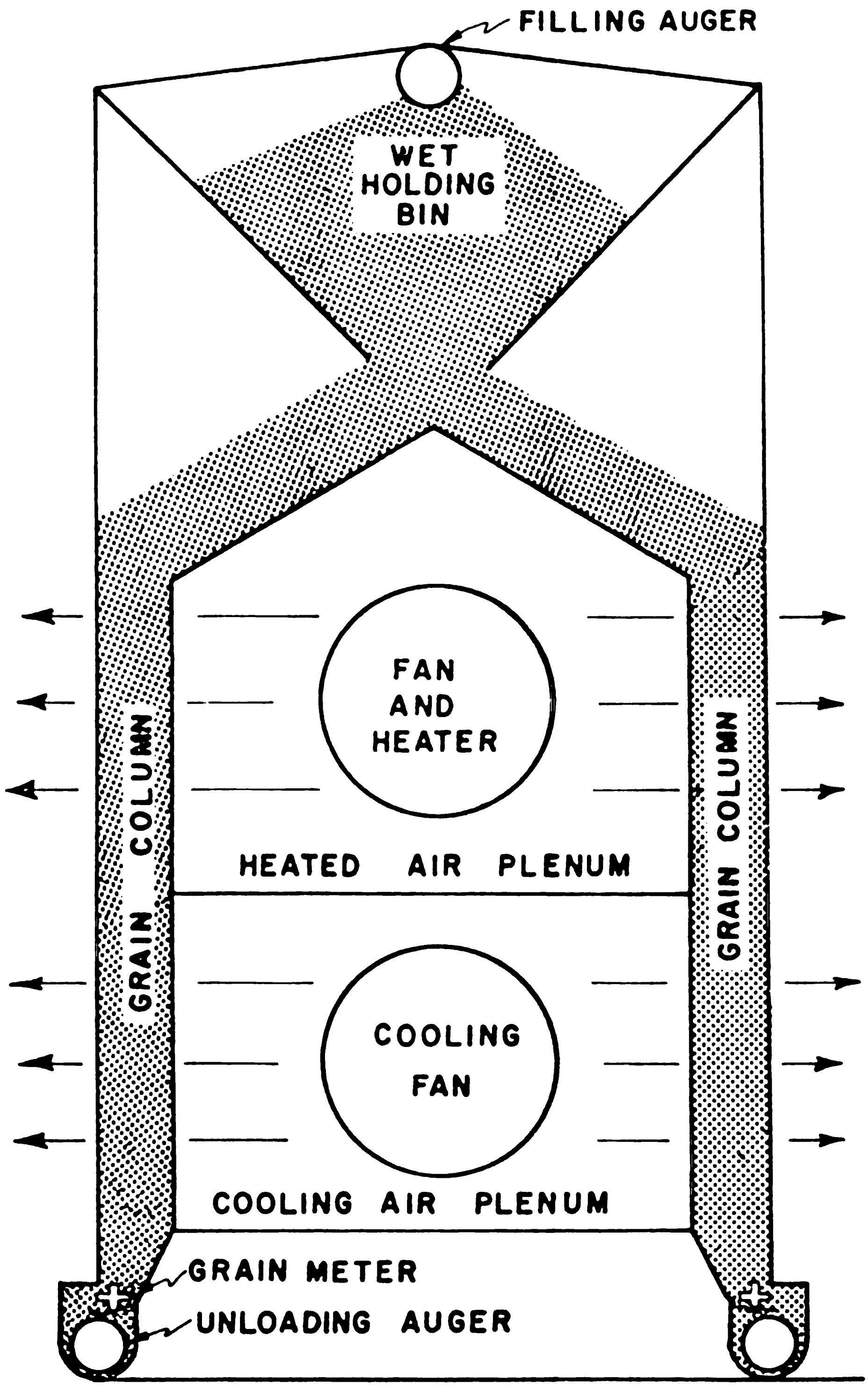


Figure 3. Schematic of a crossflow (continuous flow) grain dryer (From Brooker et al., 1974).

moisture removal. It takes about 5800 kJ/kg of water removed when the final moisture content is 25% and 6970 to 8140 kJ/kg water when the final moisture content is 15%, at an initial moisture content of about 30%. These fuel efficiencies are important when considering combination drying such as dryeration and low temperature drying when moisture is reduced in a column dryer to 18-20%.

The thicker the grain column is in a column dryer the higher is the fuel efficiency. However, thicker grain columns result in an increase in the moisture content gradient across the column.

Kirk (1959) investigated column thicknesses of 10.2, 20.3, 30.5 and 40.6 cm. He came to the following conclusions:

1. the 20.3, 30.5 and 40.6 cm columns are similar in their drying air requirements;
2. the operating costs are not significantly increased with an increase of static pressure of up to 5.08 cm of water for grain column thicknesses of 20.3, 30.5 and 40.6 cm;
3. in the static pressure range of 0.63 to 5.1 cm of water column, the drying capacity increased linearly with static pressure, there were no significant differences in drying capacity for the drying columns of 20.3, 30.5 and 40.6 cm.

The moisture and grain-temperature gradients across the dryer column and also the dryer operating costs, can be reduced either by decreasing the drying air flow rate at a constant air temperature, or decreasing the drying air temperature at a constant airflow rate (Morey et al., 1976).

2.3.2 High-Speed Continuous Cross-flow Dryers

There are two types of continuous crossflow dryers as shown in Figures 2 and 3. Crossflow dryers have a wet grain holding bin at the top. Grain flows by gravity from top to bottom through the drying and the cooling columns which are 20 to 45 cm wide. A column thickness of 30.5 cm is most common. Two fans for heated and cooling air, respectively, may be used (Figure 3). An alternative design is shown in Figure 2, where a single fan is used for heated and cooling air.

The drying rate and the final moisture content are mainly dependent upon time, air temperature, airflow rate and the initial moisture content. Moisture is usually controlled by regulating the grain flow rate by a metering auger at the bottom of the dryer, while maintaining a constant air temperature and air flowrate. The auger speed responds to a temperature sensor located in the grain column near the lower edge of the drying section.

The drying characteristics of crossflow dryers are similar to those of column batch dryers. The grain on the plenum side is overdried while that on the air exhaust side is under-dried.

The design shown in Figure 2 permits ambient air to be drawn through the grain in the cooling section; and is thus preheated as it cools the grain. This results in a 10-20% reduction of moisture gradient across the column (Bakker-Arkema et al., 1980). Some designs incorporate a metering device that causes the grain on the plenum side to move faster than the grain on the outside. Thus, the moisture content gradient is reduced.

2.3.3 Low-Temperature and Natural Air In-Bin Storage Drying

In-bin drying systems dry and cool the grain in a storage bin. In most instances the grain is left in the same bin for storage. Natural air and low temperature drying are similar processes (Bakker-Arkema et al., 1978). The difference is that no heat is added in case of the natural air system. Low-temperature drying is accompanied by raising the drying air 3 to 5.5°C above the ambient temperature by either electric heat, solar energy or other heat source (Zink et al., 1978). Liquid propane and electricity are the most common heat sources for low temperature drying; both require low capital investment. Liquid propane gas is usually not used since it requires interval timers to limit the rate of heat application (Brooker et al., 1978).

The air flow rate required for a drying system depends on the harvest date, harvest moisture, and the location. For natural air drying Brooker et al. (1978) suggested drying air flow rates of 4 m^3/min-m^3 for corn with moisture content (MC) 24-26%; 3.2 m^3/m^3-min for 22-24% MC and 2.4 m^3/m^3- min for 20-22% MC.

Adding heat, even in small amounts increases the drying capacity in a low temperature drying system. The temperature increase also encourages faster mold development. To reduce mold growth the average temperature in the bin should be below 10°C. With addition of low heat, the air flow rate can be limited to 2.4 m^3/min-m^3 for 24-26% MC grain, 1.6 m^3/min-m^3 for 22-26% MC, and 0.8 m^3/min-m^3 for 20-22% MC corn.

Although low-heat and natural air drying are slow, the quality of the finished grain is frequently high due to low application of heat. (Brooker et al., 1978).

The main disadvantage of both the low-heat and natural air in-bin drying is that the grain at the bottom is overdried, while that at the top is underdried. Drying is stopped after the average moisture content in the bin reaches a desired value. Since unloading does not allow thorough mixing and blending to obtain a uniform moisture content, the underdried corn from the top of the bin may deteriorate in storage.

Several improvements have been incorporated in in-bin drying to reduce

the vertical moisture gradient. They include, grain recirculating, removing the bottom layers when fully dried, stirring devices, and drying with alternating heated and unheated air
(Browning et al., 1971), Brooker et al., 1974).

According to Brooker et al. (1978), the fuel efficiency of all deep bin in-storage drying is high (3500 kJ/kg of water, or lower in some cases). Therefore, these systems are usually used in combination with other energy saving systems. However, low-heat and natural air in-bin drying is limited to grain that is below 25% MC.

2.4 Stirred Bin Low Temperature Corn Drying

It is well known that when drying grain by forcing air (heated or natural) through a deep bed, all of the kernels do not dry at the same rate. As the drying air moves through the bed of grain an exchange of moisture from grain to air occurs in a finite depth of grain called the drying zone. The zone moves in the direction of airflow as drying continues.

When the drying zone has completely passed through the grain, the entire mass has been dried to equilibrium with the drying air. When drying with low temperature or natural air, the time required to dry a deep bed of grain (of say over 4 m) may be more than eight weeks, depending on the initial moisture and drying conditions. The grain at the top of the bed may deteriorate by roting due to molds or due to moisture condensation. By the time the grain at the top is dried to the required moisture content, the grain at the bottom will have been overdried, especially if heated air is used for drying. Grain stirring during the drying process is one of the techniques used to rectify the overdrying of the bottom layers and the undesirable vertical moisture gradient resulting from deep bed in-bin grain drying.

Use of stirring devices was initiated in 1960; and became commercially available in 1962 (Frus, 1968; Toms, 1968, and Bern and Charity, 1978). Stirring device manufacturers claim the following advantages:
(1) increased airflow, (2) loosened grain, (3) reduced vertical gradient moisture content, (4) reduced static pressure, (5) reduced drying time, (6) reduced operating costs, and (7) better grain quality.

Field research on the overall effect of grain stirrers has been limited and the manufacturers' claims have not been entirely substantiated (Williams et al., 1978). The disadvantages of using stirring devices include condensation in the unstirred grain near the bin wall (which results in spoilage), and the extra load placed on the bin wall by the stirring devices which may require strengthening (Brooker et al., 1978).

Stirring devices most commonly consist of one or more 51-mm (2 in.) diameter, right hand, standard-pitch augers suspended from the bin-roof and side wall, and extending to near the bin floor. The augers rotate clockwise (viewed from above) and simultaneously travel horizontally around the bin and radially from near the center to near the bin wall and back. The simultaneous radial and peripheral movement of the stirring device results in a flower leaf pattern, concentric circles or spiral pattern, depending on the relative radial and peripheral velocities (see Figures 4 & 5).

The stirring auger produces small ripples on top of the stirred grain bed. Frus (1968) observed that in previously unstirred corn, the kernels are moving up the front side of the auger and down towards the bottom along the backside of the auger. It appeared that the unstirred corn is providing a "wall" against which the auger moves the corn. The ripples produced by the auger inidicate the width of the column of corn that has moved towards the bottom of the bin. Once the auger has stirred essentially all

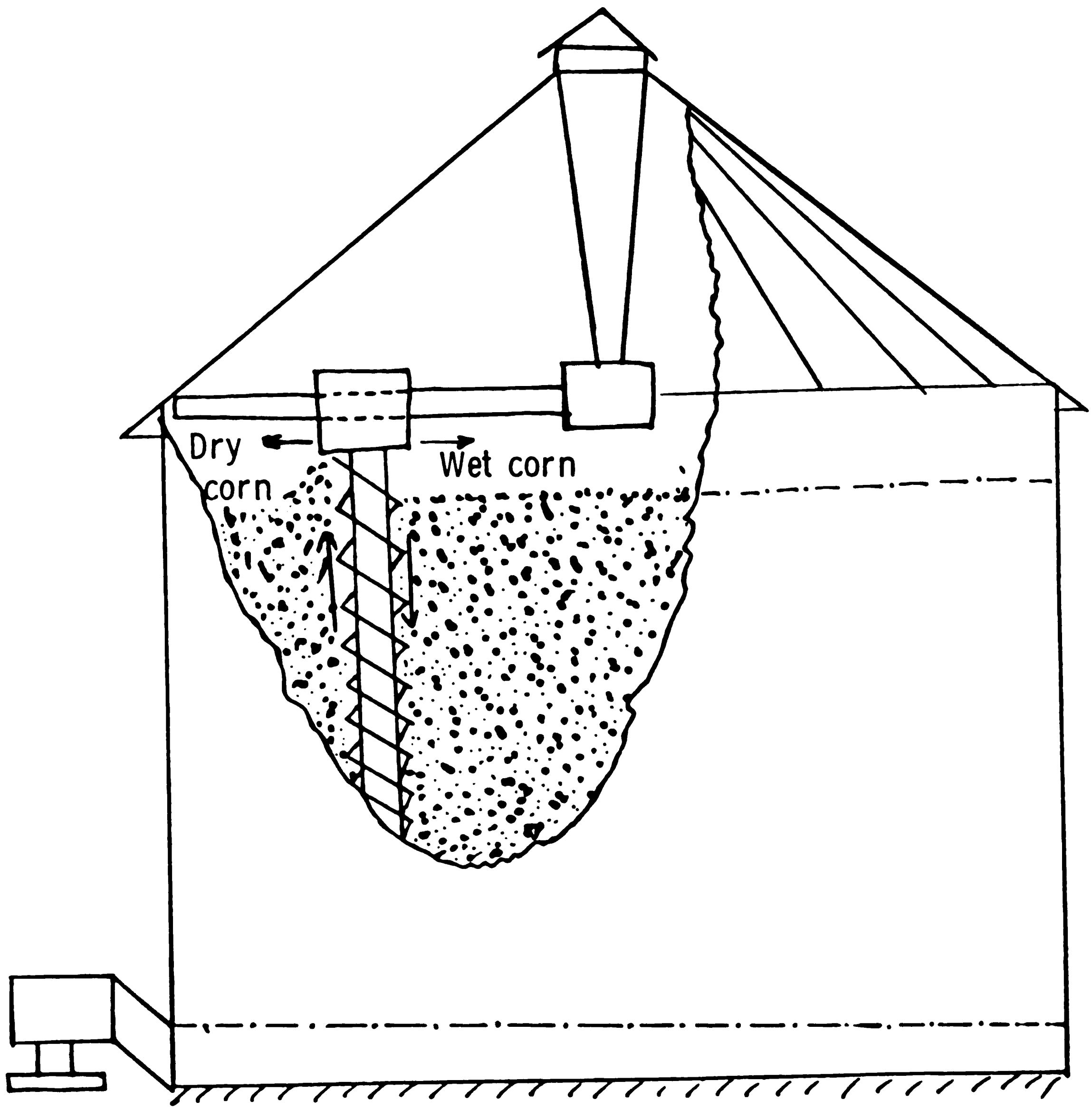


Figure 4. Schematic of grain stirring device (After Brooker et al., 1974).

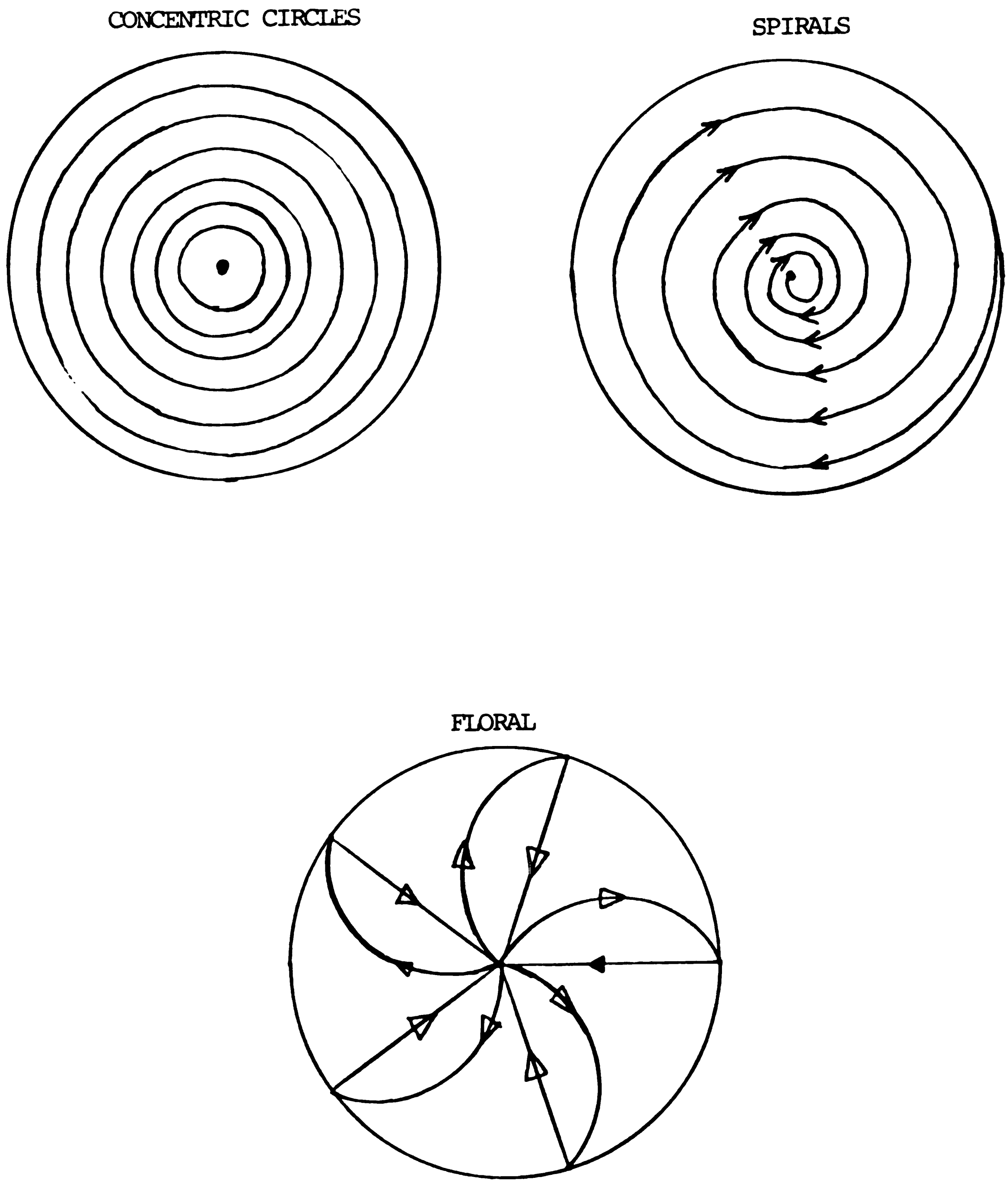


Figure 5. Top view patterns formed by single auger grain stirrer.

of the corn and has started moving through previously stirred corn, the amount of corn being moved up the front side and the amount of corn moving downwards along back side of the auger appeared to be considerably smaller.

A small circular column of grain near the bin wall is never stirred. The thickness of the column depends on how close the auger comes to the wall. It is more difficult to move air through this unstirred corn once part of the bin has been stirred (Frus, 1968).

Bern and Charity (1978) studied the disturbance effects of auger-stirring dry corn (11.3% MC). Their results indicate that the boundaries of the cross-sectional area disturbed by a stirring auger are generally parabolic in shape. The cross-sectional area decreases with increasing horizontal auger travel rate.

2.4.1 Effects of Stirring Management Techniques on Corn Drying

The available literature on stir-drying shows that the following parameters are affected by auger stirring devices: (a) grain bulk density, (b) airflow resistance and thus the airflow rate, (c) the drying time, (d) the degree of overdrying, (e) the MC gradient, (f) the drying efficiency, (g) the grain quality and thus, dry matter loss, and (i) the drying costs. The effect of stirring on the above factors depends on the stirring management, especially with respect to the frequency of stirring, the number of augers, and the auger design with respect to the rpm, the horizontal travel rate, and the auger diameter. The effects also depend on the grain condition (moisture content, foreign material, etc.) and the drying air temperature.

Bern et al. (1979) investigated the effects of auger stirring on air flow resistance and bulk density of wet and dry shelled corn at 22.6% and 14.6% MC, respectively, and drew the following conclusions: (1) auger stirring decreases in situ bulk density of wet corn by 7.9% and of dry corn by 6.9%, when placed in a bin with a mechanical spreader, (2) auger stirring increases in situ bulk density of dry gravity-placed corn by 2.4%, and 3 left unchanged that of wet gravity-placed corn.

It is reasonable to expect an increase in airflow rate with stirring. Stirring loosens pockets of trash and fines, and decreases the bulk density of corn; thus, a decrease in pressure drop with stirring. It is not possible to specify the increase in airflow rate resulting from a decreased static pressure drop with stirring. The increase is a function of fan size and fan characteristic curve (Williams et al., 1978). Baker et at. (1979) observed an increase in airflow rate of 3% with stirring. Bern (1973) (cited by Williams et al. (1978) developed the following empirical equation for pressure drop in stirred grain:

$$\frac{\Delta P}{L} = (0.0484\rho_b - 0.1274)\ v^2 + (4.033\,\rho_b - 10.12)\ v + 12.91 - 1310\rho_b \qquad [2.1]$$

Bern observed a 10% increase in airflow rate after stirring.

The best way to measure the change in airflow with stirring is to measure the pressure drop and use the fan curve to determine the airflow. Alternatively, especially for simulation purposes, the airflow may be determined by an iterative procedure balancing the air velocity and pressure drop, assuming that the fan output and efficiency remain the same before and after stirring.

The effects of stir drying on drying time and drying efficiency has been studied by several researchers. All literature available indicates that intermittent stirring reduces drying time, but also reduces the drying efficiency. Drying efficiency is defined as the ratio of the amount of moisture removed from the dried grain to the amount necessary to saturate the drying air adiabatically. Continuous stirring reduces the drying rate during relatively poor weather, and reduces the drying efficiency in all conditions as compared with unstirred drying at the same conditions (Baker et al., 1979). According to a simulation study on stir-drying by Colliver et al. (1979), continuous stirring reduces drying time in all cases, but the reduction in drying time is less with relatively unfavorable weather. Their results indicate that stirring once a day required the shortest drying time. They observed no significant differences for other methods (constant stirring and stirring once a week) except stirring once at the beginning of the drying process. They found that stirring once while drying in good weather was just as good as constant stirring, daily stirring and stirring once a week. Williams et al. (1978) concluded that drying time was the same when stirring at 5, 10 and 15-hour intervals.

The most important advantage of stirring is decreasing the overdrying at the bottom layers, thus resulting in a uniform moisture throughout the bin. Overdrying decreases and moisture uniformity increases with stirring frequency. The combined effect of shorter drying time, less overdrying and more uniform moisture content results in decreased mold damage, less dry matter loss and therefore, better corn quality (Baker et al., 1979; Colliver et al., 1979; Frus, 1968; and Williams et al., 1979). Moreover, the combined reduced drying time and decreased overdrying results in less energy consumption and therefore, reduced drying costs, (Baker et al., 1979).

Williams et al. (1978) concluded the following about the stir drying of corn:

(1) a stirring device allows drying at less than favorable drying conditions such as lower airflow rates, higher drying tempera-

ture and greater bed depths (compared to unstirred drying) without spoilage;

(2) the additional costs for a stirring device cannot be justified based on the same equal fill depths or equal weight of grain in unstirred bin; and

(3) the use of a stirring device allows a greater bed depth with per bushel costs equal to unstirred bin at a lower grain depth. The additional stirring device cost can be justified in this situation.

The above literature review shows that stirring devices are beneficial for in-bin grain drying. Intermittent stirring has been shown to perform better and costs less to operate than continuous stirring. According to Baker et al. (1979) intermittent stirring (24 hours per week) results in a higher degree of mixing and higher drying efficiency than continuous stirring. Frus (1968) attempted to explain these phenomena by observing that once stirred, there was less upward and downward movement of kernels during subsequent stirring. The optimum stirring frequency depends on the drying air and grain conditions and thus varies from bin to bin and from year to year.

2.5 Low-Temperature and Natural-Air In-Bin Drying Theory and Simulation

Much research has been done to study the processes by which water is removed from biological materials. The drying process consists of simultenous heat and moisture transfer. Henderson and Perry (1966) and Brooker et. al. (1974) described the constant rate of drying during the initial drying period followed by a falling-rate drying period. The constant-rate period for extremely moist single kernel drying can be expressed by (Brooker et al., 1974):

$$\frac{d\,M}{d\,t} = \frac{h_d' A}{R_v T_{abs}} (P_{v\,wb} - P_{v\,\infty} = \frac{h' A}{h_{fg}} (T_{\infty} - T_{wb}) \qquad [2.2]$$

Prediction of the drying rate during the falling-rate period is more complicated than during the constant-rate period. Semi-theoretical and empirical relationships for predicting behavior of cereal grains during the falling-rate period have been proposed and used by several researchers and dryer designers.

Brooker et al. (1974) indicated six possible modes of moisture removal from cereal grains: (a) liquid movement due to surface forces (capillary flow); (b) liquid movement due to moisture concentration differences (liquid diffusion); (c) liquid movement due to diffusion of moisture on the pore surfaces (surface diffusion); (d) vapor movement due to moisture concentration differences (vapor diffusion); (e) vapor movement due to temperature differences (thermal diffusion); and (f) water and vapor movement due to total pressure differences (hydrodynamic flow). The exact manner in which water leaves the grain is dependent upon drying air temperature, air velocity, moisture concentration, and product type and condition (Stevens et al., 1978).

Based on the above modes of moisture removal, Luikov (1956) and his co-workers in the Soviet Union developed the following systems of differential equations for describing the drying of capillary porous products:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12}\, \theta + \nabla^2 K_{13}\, P$$

$$\frac{\partial \theta}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22}\, \theta + \nabla^2 K_{23}\, P$$

$$\frac{\partial P}{\partial t} = \nabla^2 K_{31} M + \nabla^2 K_{32}\, \theta + \nabla^2 K_{33} P \qquad [2.3]$$

where K_{11}, K_{22}, and K_{33} are phenomenological coefficients. The other K values are coupling coefficients. Luikov's equations can be simplified by neglecting the pressure and temperature gradients in a corn kernel during the drying and rewetting processes. This results in:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M \qquad [2.4]$$

The transfer coefficient K_{11} is called the diffusion coefficient, D. If D is constant, equation [2.4] reduces to:

$$\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial r^2} + \frac{c}{r} \frac{\partial M}{\partial r} \qquad [2.5]$$

where c is zero for planar symmetry, 1 for a cylindrical body, and 2 for a sphere. In solving equation [2.5], the following boundary conditions are often assumed:

$$M_{(r,o)} = M_o \qquad [2.6]$$

$$M_{(r_o,\ t)} = M_e \qquad [2.7]$$

The analytical solution of equation [2.5] for the average moisture content of various regularly shaped bodies can be obtained directly by integration (Crank, 1957). For an infinite plane with boundary conditions [2.6] and [2.7] , the solution is:

$$MR = \frac{8}{\Pi^2} \sum_{n=o}^{\infty} \frac{1}{(2n+1)^2} \exp\left[- \frac{(2n+1)^2 \Pi^2}{9} x^2 \right] \qquad [2.8]$$

for a sphere:

$$MR = \frac{6}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left[- \frac{n^2 \Pi^2}{9} x^2\right] \qquad [2.9]$$

and for a finite cylinder:

$$MR = \sum_{n=1}^{\infty} \frac{4}{\lambda_n^2} \exp - \frac{\lambda_n^2 x^2}{4} \qquad [2.10]$$

where

λ_n are the roots of the Bessel function of zero order (Perry et al., 1963).

In the above equations the average moisture content and the time are expressed as dimensionless quantities, MR and x, respectively:

$$MR = \frac{M - M_e}{M_o - M_e} \qquad [2.11]$$

$$X = \frac{A}{V} (Dt)^{1/2} \qquad [2.12]$$

where A represents the surface area and N the volume of the body. For a plane, A/V equals half-thickness; for a sphere A/V equals (radius)/3; for a cylinder A/V equals (radius)/2. Chu and Hustralid (1968) concluded that the equations [2.8] through [2.12] describe the drying rate of a solid satisfactorily in the moisture ratio, (MR) range of $\geq$ 0.4.

Chu and Hustralid (1968) studied diffusion of moisture in corn kernels assuming that the kernel could be represented by a sphere of equivalent radius R. The specific conditions were as follows:

(1) relative humidity 10-70%

(2) air temperature 49°C - 71°C

(3) corn moisture content 5 - 35% (dry basis).

For a moisture content dependent diffusivity, the following equation was recommended:

$$\frac{M - M_e}{M_o^* - M_e} = \frac{6}{\Pi^2} \exp [- \frac{\Pi^2}{R^2} D\ t\ ] \qquad [2.13]$$

where

$$D = 1.513 \exp \quad (0.045\, T_{abs} - 5.485)M - \frac{2513}{T_{abs}} \qquad [2.14]$$

$$M_o^* = 1.0655 M_o - 0.0108 \qquad [2.15]$$

$$R = \frac{3L\ W\ K}{2(LW+WK+LK)} \qquad [2.16]$$

where T_{abs} is the absolute temperature °K, and L, W, K are the length, width, and thickness of the average kernel respectively. All the above equations work satisfactorily under the test conditions. However, for drying temperatures such as encountered in low temperature and natural air drying, several of coefficients of Chu and Hustrulid have been changed for use under low-temperature conditions (Rugumayo, 1979).

2.5.1 Thin-Layer Drying Equations for Corn

Thompson et al. (1968) developed an empirical thin layer drying equation for corn in the range of 60 to 150°C:

$$t = A \ln MR + B\ (\ln MR)^2 \qquad [2.17]$$

where: $$A = 0.004888 - 1.86178 \qquad [2.18]$$

$$B = 427.3640 \exp\ (-0.033\theta) \qquad [2.19]$$

The most commonly used thin layer equations are modified versions of the Thompson equation (Brooker et al., 1974; Pfost et al., 1976). The equations have not proved to be totally satisfactory (Rugumayo, 1979).

Flood et al (1969), Troeger and Hukill (1970), Muh (1974), and Misra (1978), developed emprical drying equations for corn in the temperature ranges of (a) 2.2°C to 21.1°C, (b) 32 to 71°C and 27 to 104°C, respectively.

Flood et al. (1969):

$$MR = \exp\left(-kt^{0.664}\right) \qquad [2.20]$$

where

$$MR = \frac{M - M_e}{M_o - M_e}$$

$$k = \exp\left(-xt^{y}\right)$$

$$x = (6.0142 + 1.453 \times 10^{-4}(rh)^2)^{0.5}$$

$$(1.8\theta + 32)(3.352 \times 10^{-4} + 3 \times 10^{-8}(rh)^2)^{0.5}$$

$$y = 0.1245 - 2.197 \times 10^{-3}(rh) - (1.8\theta + 32)$$

$$(2.3 \times 10^{-5}(rh) + 5.8 \times 10^{-5})$$

Troeger and Hukill (1970):

$$\frac{t}{60} = P_1(M-M_e)^{q_1} - P_1(M_o-M_e)^{q_1} \text{ for } M_o \geq M \geq Mx$$

$$\frac{t}{60} = P_2(M-M_e)^{q_2} - P_2(M_x - M_e)^{q_2} + t_{x_1} \text{ for } M_{x_1} > M \geq M_{x_2}$$

$$\frac{t}{60} = P_2(M-M_e)^{q_3} - P_3(M_x - M_e)^{q_3} + t_{x_2} \text{ for } M_{x_2} > M \geq M_e \qquad [2.21]$$

where

$$M_{x_1} = 0.40\ (M_o-M_e) + M_e$$

$$M_{x_2} = 0.12\ (M_o-M_e) + M_e$$

$$t_{x_1} = [P_1(M_{x_1}-M_e)^{q_1} - P_1(M_o-M_e)^{q_1}]/60$$

$$t_{x_1} = [P_2(M_{x_2}-M_e)^{q_2} - P_2(M_{x_1}-M_e)^{q_2}]/60 + t_{x_1}$$

$$P_1 = \exp(-2.45-6.42\ M_o^{1.25} - 3.15\ (rh) + 9.62\ M_o(rh)^{0.5}$$

$$+ 0.054\theta - 0.036\ Va + 0.96$$

$$P_2 = \exp[2.82 + 7.49\ (rh + 0.01)^{0.67} - 0.0322\theta - 0.5728$$

$$P_3 = [0.12(M_o-M_e)]^{(q_1-q_3)}(P_2q_2/q_3)$$

$$q_1 = -3.468 + 2.87\ M_o - [0.019/(rh + 0.015)] + 0.0288\theta$$

$$q_2 = -\exp(0.81 - 3.11rh)$$

$$q_3 = -1.0$$

Muh (1974):

$$t = A\ln MR + B\ (\ln MR)^2 \qquad [2.22]$$

where

$$A = -3.287 - 0.1044\theta\ (37.7°C < \theta \leq 60°C)$$

$$B = -3.34114 + 0.1286\theta\ (37.7°C < \theta \leq 60°C)$$

$$A = -8.2075 + 0.079830\theta\ (60°C < \theta \leq 82.2°C)$$

$$B = 0.44881 - 0.004170\theta\ (60°C < \theta \leq 82.2°C)$$

$$A = -4.69252 + 0.037060\theta\ (82.2°C < \theta \leq 104.0°C)$$

$$B = -7.75868 + 0.023150\theta\ (82.2°C < \theta \leq 104.0°C)$$

The following is the Misra (1978)

$$M = (M_o-M_e)\ \exp[-(\exp(-7.1735 + 1.2793\ \ln(1.8T + 32)$$

$$+ 0.0061v))\ t(0.0811\ \ln(rh) + 0.0078\ M_o)] + M_e \qquad [2.23]$$

where

T is drying air temperature, °C

v is air flow rate in meters, per minute

rh is air relative humidity, decimal

t is time in hours.

Only the Flood equation (also called Sabbah equation) and possibly the Muh equations, would appear of interest for use for low-temperature and natural air corn drying. These equations are empirical. Rugumayo (1979) developed an equation from mathematical diffusion theory similar to the model presented by Chu and Hustrulid (1968):

$$M_t = (M_o - M_e)\ \exp[(25.592 - 38.6298\ M_{t-1} + 26.6824\ \ln\ (M_{t-1})$$

$$- 0.0044\theta_t\ (M_{t-1})\ \exp(rh_t)^2 t] + M_e \qquad [2.24]$$

The moisture content predicted by equation [2.24] was compared with the Flood equation [2.20] and the Misra (1978) equation. When compared with actual experimental data the Rugumayo equation gave better results than either Flood or Misra equations (Rugumayo, 1979).

2.5.2 Corn Moisture Adsorption

Natural air grain drying is risky due to changing weather conditions. Grain may be rewetted by high humidity air at night or rainy days. Therefore it is necessary to account for grain moisture adsorption for proper evaluation of in-bin low temperature and natural air drying. Understanding of the adsorption kinetics provides useful information in grain quality and a guide for grain conditioning, storing, processing and fumigating. In grain rewetting studies, del Guidice (1959) developed the following empirical equation for rewetting of corn:

$$MR = \exp[-4.309\ (PS)^{0.466(rh)}\ (rh)^3 \Delta t] \qquad [2.25]$$

where

$$MR = \frac{M_t - M_e}{M_{t-1} - M_e}$$

The equation was tested at 15.6° C to 40.6° C dry bulb temperatures, 60% to 100% relative humidity, and air velocities of 3 mpm and 12.2 mpm. The del Guidice equation does not perform satisfactorily at air conditions outside these ranges (Rugumayo, 1979). The following equation for grain rewetting relationship was developed by Rugumayo:

$$M_t = (M_o - M_e)\ \exp[(162.1179 - 487.9552\ M_{t-1} + 118.6144\ \ln (M_{t-1}) + 0.696580\theta_t\ (M_{t-1})^2\ \exp\ (rh_t^2) t] + M_e \qquad [2.26]$$

The equilibrium moisture content (M_e) in the above equation must be calculated from the DeBoer's equilibrium moisture content equations for shelled corn (Bakker-Arkema et al., 1974).

2.5.3 In-bin Low-temperature Drying

Low-temperature and natural air drying simulation models have been proposed by several authors (Flood et al., 1969; del Guidice, 1959; Thompson, 1968; and Bakker-Arkema et al., 1977).

Brooker et al. (1974) analyzed in-bin drying by making energy and mass balances on a differential volume (Sdx) located at an arbitrary location in the stationary bed. The following set of three differential equations was obtained assuming the air and grain temperatures are equal:

(a) for the enthalpy of air and product

$$\rho_p (C_p + MC_w) \frac{\partial T}{\partial t} + G_a[(C_a + HC_v) \frac{\partial T}{\partial t} + G_a (C_w - C_v)(100-T)$$

$$+ h_{fg}] \frac{\partial H}{\partial x} = 0 \qquad [2.27]$$

(b) for the humidity of the air

$$\rho_p \frac{\partial M}{\partial t} + G_a \frac{\partial H}{\partial x} = 0 \qquad [2.28]$$

and

(c) for the moisture content

$$\rho_p \frac{\partial M}{\partial t} = \text{an appropriate kin layer equation.} \qquad [2.29]$$

Equations [2.26] through [2.29] are the basic equations for simulating fixed bed grain drying. The equations can be solved with the help of a digital computer by writing the equations in a finite difference form. Four possible finite difference methods for computing the numerical derivatives in the model are discussed by Bakker-Arkema et al. (1977).

When equations [2.27] through [2.29] are written in implicit finite difference form the following equations are obtained:

$$\rho_p(C_p + C_w M_{x,t-\Delta t}) [\frac{T_{x,t} - T_{x,t-\Delta t}}{\Delta t}] + G_a[C_a + C_v H_{x-\Delta x,t}]$$

$$[\frac{T_{x,t} - T_{x-\Delta x,t}}{\Delta x}] = G_a [\frac{H_{x,t} - H_{x-\Delta x,t}}{\Delta x}] [(C_w - C_v)(T_{x,t} - 100)$$

$$-h_{fg}] \qquad [2.30]$$

$$\rho_p[\frac{M_{x,t} - M_{x,t-\Delta t}}{\Delta t}] + G_a [\frac{H_{x,t} - H_{x-\Delta x,t}}{\Delta x}] = 0 \qquad [2.31]$$

$$\rho_p \left[\frac{M_{x,t} - M_{x,t-\Delta t}}{\Delta t}\right] = r_m \left[T_{x,t},\ H_{x,t},\ M_{x,t-\Delta t}, t\right] \qquad [2.32]$$

Equations [2.30] through [2.32] can be rearranged to obtain three equations which are explicit functions of $H_{x,t}$:

$$T_{x,t} = \frac{G_a \Delta t (C_a + C_v H_{x-\Delta x,t}) T_{x-\Delta x,t} - \Delta t G_a (H_{x,t} - H_{x-\Delta x,t})(C_w - C_v) + \rho_p \Delta x (C_w M_{x,t-\Delta t}) T_{x-\Delta x,t}}{-G_a \Delta t (H_{x,t} - H_{x-\Delta x,t})(C_w - C_v) + \rho_p \Delta x (C_p + C_w M_{x,t-\Delta t}) + G_a \Delta t (C_a + C_v H_{x-\Delta x,t})} \qquad [2.33]$$

$$M_{x,t} = \frac{G_a \Delta t}{\rho_p \Delta x} (H_{x,t} - H_{x-\Delta x,t}) + M_{x,t-\Delta t} \qquad [2.34]$$

$$M^*_{x,t} = r_m (T_{x,t},\ H_{x,t},\ M_{x,t-\Delta t},\ t) \qquad [2.35]$$

The moisture content $M^*_{x,t}$ in equation [2.35] can be obtained using either a drying or rewetting thin-layer equation.

The complexity of the pychrometric conditions in the drying or rewetting equation call for use of a search for the value of H_x, t which gives agreement in all the three equations simultaneously (Bakker-Arkema et al., 1977). The search algorithm developed by Bakker-Arkema et al. (1977) is outlined below:

(1) Set initial $H_{x,t} = H_{x-\Delta x,t}$;

(2) Calculate $T_{x,t}$ from equation [2.33];

(3) If $RH_{x,t} < 100\%$ go to step (5);

(4) Simulate condensation to find $T_{x,t}$; set flag;

(5) Calculate $M_{x,t}$ from [2.34];

(6) If condensation flag is set, exit;

(7) Calculate $M^*_{x,t}$ from equation [2.35].

The search terminates when H has reached a specified value of absolute humidity. The corresponding value of T and M are then computed from equations [2.33] and [2.34] respectively.

The fixed bed equations are first evaluated at each node through the depth of the dryer and then are incremented one time step. At the end of each depth iteration, the average moisture content and dry matter decomposition are computed.

The equations for dry matter decomposition have been developed by Thompson (1972) and are based on the work by Steele et al. (1969), who developed a quantative relation between the carbon dioxide production of shelled corn (dry matter loss due to grain respiration and mold growth) and time, temperature, moisture content and mechanical damage. The dry matter decomposition equation is:

$$DM = 0.0883\ (\exp(0.006\ TEQ)-1) + 0.00102\ TEQ \qquad [2.36]$$

$$TEQ = \Delta t/AM_m . AM_T \qquad [2.37]$$

$$AM_m = 0.103\ [\exp(455/M_{DB} \cdot 1 \cdot 53) - 0.0084\ M_{DB} + 1.558]$$

$$\text{for } 13 \leq M \leq 35 \qquad [2.38]$$

$$MT' = 32.3/\exp(0.1044\theta+1.856)$$

$$AM_T = MT'$$

$$\text{for } \theta \leq 15.5° \text{ C or } M < 19\% \qquad [2.39]$$

$$AM_T = MT' + [(M-19)/100]\ \exp(0.0183\theta-0.2847)$$

for $\theta > 15.5°$ C and $19 < M \leq 28\%$ [2.40]

$$AM_T = MT' + 0.09\ \exp(0.0183\theta-0.2847)$$

for $\theta > 15.5°$ C and $M > 28\%$ [2.41]

According to Saul (1970):

$$AM_T = 128.76\ \exp(-0.1404\theta-2.496)$$ [2.42]

for $\theta \leq 15.5°$ C.

where:

AM_T, AM_T are dimensionless multipliers for moisture content and temperature respectively

TEQ is the equivalent reference time, hr

Δt is the drying time interval, hr

2.6 Low Temperature, In-bin Stir Drying Theory and Simulation

A fixed bed grain drying model developed at Michigan State University (Bakker-Arkema et al., 1974; Rugumayo, 1979) was modified to simulate stir drying. The model uses equations [2.24], [2.26] and the DeBoer's equation (Bakker-Arkema et al., 1974) for drying rewetting and equilibrium moisture content, respectively. The model operates in accordance with the search algorithm developed by Bakker-Arkema et al. (1977) and outlined in section 2.7.2.

The following assumptions were made:

1. Stirring is instantaneous and there is no vertical moisture content gradient; all corn and air properties (within the grain) are equal to average conditions prior to stirring.
2. Due to the low drying air temperatures, the corn is assumed to be of the same temperature as the air.
3. The increase in air flow rate after stirring is negligible.

To study the effect of stirring on drying time and dry matter loss, the actual East Lansing (at the Department of Agricultural Engineering, Michigan State University) hourly weather data for November 1976 was used for simulating different stirring methods for the following conditions:

- bin diameter 1.6 m, height 2.13 m
- fill depth, 1.83 m (grain volume 1.13 m^3)
- air flow rate 2.85 m^3/m^2 and 5.7 m^3/m^2

- temperature range 5.6-24.5° C
- relative humidity range 17 to 70%

The results of this simulated study indicated that periodic stirring results in shorter drying time and higher grain quality (as indicated by less dry matter loss) than continuous stirring if poor drying weather conditions prevail; in favorable weather conditions continuous stirring does not perform any better than intermittent stirring (see Table 5). Similar results have been reported by other researchers (Baker et al., 1979; Colliver et al., 1979; Williams et al., 1978; and Bern et al., 1979).

Frus (1968) observed little mixing of previously stirred corn. Baker et al. (1979) concluded that continuous stirring reduces drying efficiencey and drying rate, and therefore the amount of water removed per given time. The optimum frequency of stirring depended on drying conditions such as drying air temperature and relative humidity and corn moisture content and percentage of fine and foreign materials.

Table 5. Effect of stirring management on drying time and dry matter loss (airflow rate 5.7 m^3/m^2).

No. of stirs	Stirring control method	Ave. MC WB	Dry matter loss %	Drying time hrs
3	Stir after 60, 120 and 216 hrs	15.47	0.034	232
4	Stir every 48 hrs	15.49	0.032	232
6	Every 24 hrs if MC at bottom is less than 16% WB	15.49	0.031	232
9	Every 24 hrs	15.48	0.025	221
∞	Continuous	18.49	0.038	313

3. EXPERIMENTAL

The research reported in this thesis was carried out at the Kalchik Farms in Bellaire, Michigan, as a part of a continuing investigation on alternative on-farm grain drying methods in Michigan. The following five alternative drying systems have been tested by Michigan State personnel (Bakker-Arkema et al, 1979-1980; Silva et al, 1979; Silva, 1980; and Kalchik et al, 1979):

1. high temperature/natural air combination drying;
2. high temperature/low temperature (electric heat) with and without stirring combination drying;
3. in-bin dryeration;
4. in-bin counterflow drying; and
5. conventional batch drying.

Kalchik Farms was chosen as the site for grain drying research because of the high harvest moisture content and unfavorable climatic conditions during harvest. It can be argued that any drying technique that operates successfully in Bellaire, Michigan, will work at any farm in the lower peninsula of Michigan.

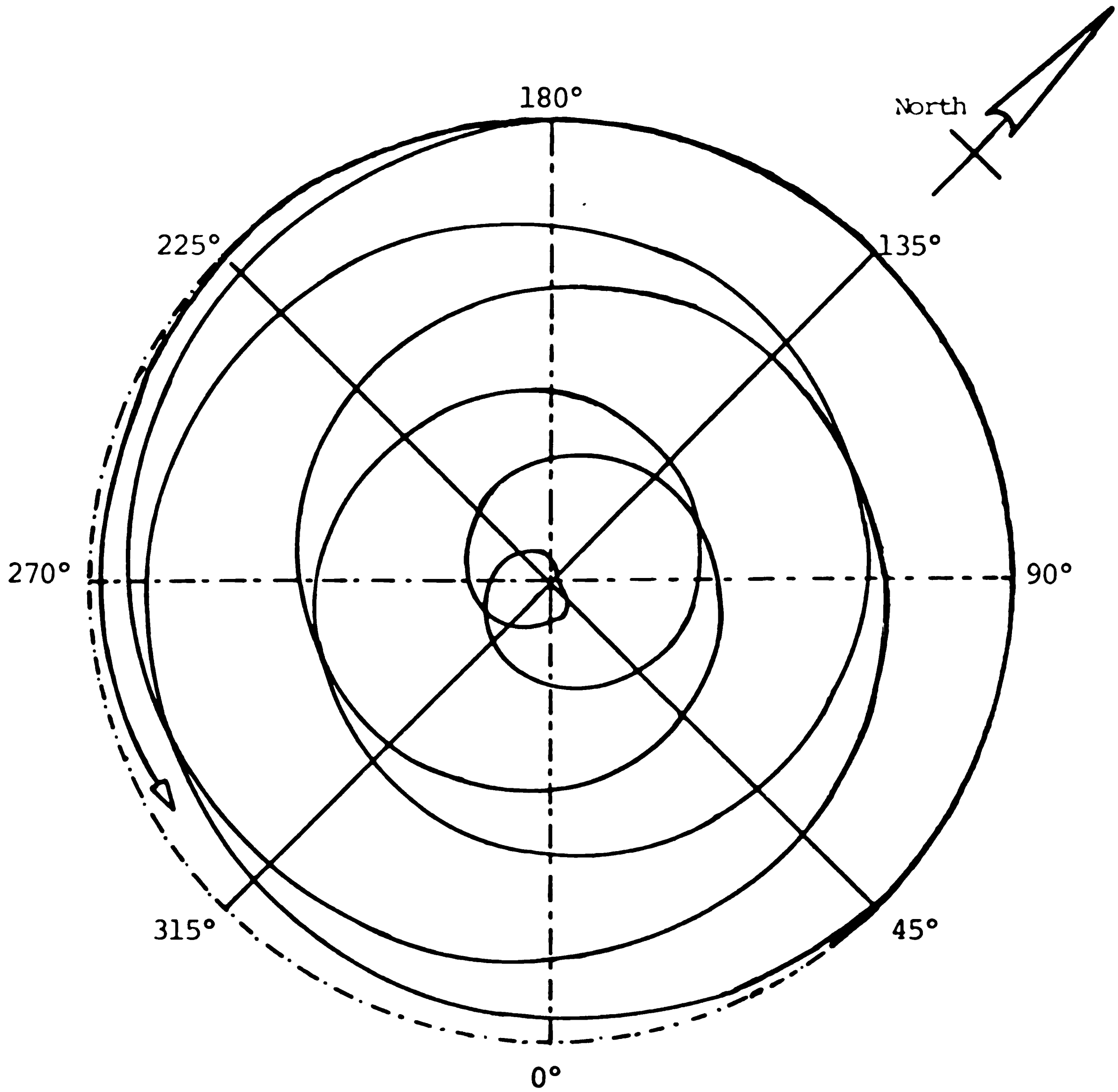
For the low-temperature in-bin combination drying research a single auger stirring device is used. The stirring device is a grain Stir-ator model 179 manufactured by the David Manufacturing Company, Mason City, Iowa. It has a single 51 mm (2 in) diameter right hand constant pitch auger with a 25mm (1 in) shaft. When stirring corn 3.67m (12 ft) deep, the 1.1 kW (1.5HP) motor drives the auger at about 500 rpm; the average tangential travel speed is

5.4 m/hr and the average radial travel speed is 1.7 m/hr. (In an empty bin the average tangential travel speed is 25.2 m/hr and the average radial travel speed is 6.8 m/hr). At a corn depth of 3.67m the auger travels horizontally in a spiral pattern as illustrated in Figure 6. The auger remains at the inside bin wall during half of a revolution to improve the stirring of the grain next to the wall.

The corn (variety DeKalb XL12) to be dried by the high/low-temperature stir drying process (LT-ST) was harvested at between 32 and 35% moisture content, wet basis (MC-WB). Before the test the corn was cleaned using a Farm Fans rotary cleaner and loaded into a wet holding bin (capacity 2.54 tons) with a 12.5m New Idea Flight elevator. From the wet holding bin the corn was loaded into a Kan-Sun (model 8-15-10) continuous crossflow dryer through a 0.15m diameter, 4.88m long screw auger. The corn was dried to 23-24% MC-WB at 104.4°C at airflow rate of 80.68m per minute per m^3 of grain. The corn was loaded into the low-temperature, stir drying bin through a 0.15m, 12.8m screw auger. A Farm Fans mechanical spreader was used to spread the corn evenly into the 5.5m (18 ft)-diameter, 3.7 high bin.

The LT-ST bin was loaded first with about 1.8m of corn, after which a natural air (NA) bin (5.5m-diameter) was filled with the same amount of grain for comparison. This meant that the upper 1.8m of grain was placed in each bin after the bottom portion had been partially dried for 1 1/2 days at about twice the (full bin) designed airflow rate. Both the LT-ST and the NA bins were filled to a total depth of 3.67m, equivalent to $86.5m^3$ (2444 bushels) of corn.

After filling the LT-ST bin with the last 1.83m, the grain was immediately leveled and stirred for 10 hours to equalize the moisture content



Grain Depth: 3.67m (12 ft)
Bin Diameter: 5.5m (18 ft)
Auger Horizontal Travel Rate: 5.66m/hr

Figure 6. Path of auger horizontal travel.

throughout the bin. The average grain properties after the stirring were considered the initial conditions for the drying test.

Drying air for the LT-ST bin was heated by a 20 kW Aerovent electric heater to 4 to 6°C above ambient temperature, and pushed through the grain at the rate of 1.6m^3 per min/m^3 (2 cfm/bu of grain) using a 2.24 kW (3 HP) vane axial Aerovent fan. Ambient air was pushed through the grain in the NA bin at the rate of 2.0 m^3 per min/m^3 (2.5 cfm/bu) using a 3.73 (5 HP) kW centrifugal fan.

The average ambient temperature was 4.5°C and the relative humidity varied from 70 to 100% during the test (November 5th to 28th, 1979).

The stirring device was turned on for six hours every 48 hours. During a six hour stirring interval the auger travels from the periphery of the bin to the center and back twice, and makes ten revolutions around the bin. This appears to be sufficient to completely stir and mix the grain in the bin. Previous computer simulations had demonstrated that stirring every 48 hours is to be preferred over continuous stirring (See Section 2.8).

The following parameters were measured before and after stirring, at the top, middle and the bottom of the bin:

1. grain moisture content, before and after drying;
2. grain test weight;
3. grain quality as determined by the proportion of broken kernels and foreign materials (BCFM), stress cracks, resistance to breakage, and viability;
4. air flow rate and inlet temperature; and
5. energy consumption (of the fan, heating and stirring device).

3.1 Instrumentation and Measurement

The grain moisture content was measured with a recently calibrated "Steinlite" moisture meter. The moisture content of all samples was checked with a GAC II Dickey-John moisture meter which has been calibrated against the standard oven method (Brooker et al., 1974).

The temperatures were measured with copper-constantan thermocouples and recorded with a Texas Instrument data logger.

Sample quality evaluation was performed using standard methods for stress cracks (Thomson and 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).

The airflow rate was determined from fan curves supplied by the fan manufacturer, after measuring the static pressure in the false floor of the bins. The electrical power usage was measured with a kWh-meter supplied by the electric power company.

3.2 Economic Analysis

An economic analysis computer model, TELPLAN (Harsh et al., 1978) was used to calculate a ten year budgeting analysis for drying 381 tons (15000 bushels) per year using LT-ST, NA, and non-stirred low-temperature drying (LT-NS). The break even drying costs for the three systems were compared.

3.3 Drying Computer Simulation

The computer simulation model described in Section 2.8 was used to simulate corn drying using weather data obtained on the experimental site. In addition to the assumptions outlined in Section 2.8, it was assumed that there was no increase in airflow rate after stirring during the 1979 test. This assumption is not generally valid since a stirring device loosens the grain and therefore, tends to increase the airflow rate. Some investigators have observed a 3 to 33% airflow rate increase after stirring (Williams et al., 1979; Bern et al., 1979; and Baker et al., 1979). The airflow increase is dependent upon the fan characteristic curve and the amount of fines and foreign materials in corn, and the corn depth. During the 1979 test, the corn was high in foreign matter and there was no detectable static pressure difference before and after stirring. In 1980, a 25% increase in airflow rate was observed (124.6 m^3 before and 155.7 m^3 after stirring).

4. RESULTS AND DISCUSSIONS

4.1 Effect of Stirring on Drying Time and Moisture Content Distribution

The actual moisture content distribution in the LT-ST and NA systems as a factor of time and bin depth is given on Table 6. Similar simulated results are given on Table 7. As can be seen on Table 6, drying from about 23.7% to 15% MC-WB took three weeks (504 hrs fan operation) in the LT-ST system in the fall of 1979.

The fan on the NA bin was operated 600 hours in the fall before the low-temperature ambient conditions prevented further blowing. The moisture content at the top of the bin was 21.2 percent at that time. Drying was re-started for a few days in February when the ambient conditions in the Bellaire area reached an uncommonly high temperature (65°F or 18°C). The warm weather caused slight molding of the corn at the top of the bin. About 2.4 tons (100 bushels) of the grain were removed, mixed with dry corn and (without problems) used as cattle feed. Final drying of the NA bin commenced on April 13 and was completed within a week. The 5 HP centrifugal fan had operated for 1525 hours. The average final moisture content was 16.2 percent with a MC in the top and bottom of the bin of 16.7% and 15.7%, respectively, after removing the top 2.4 tons of wet moldy corn.

In the fall of 1980 it took eleven days (264 hours) to dry corn from 21.76% to 15.52% in the low-temperature stir drying system. The shorter drying time (compared with three weeks in the fall of 1979) was partly due to the favorable drying weather, cleaner corn and therefore, higher airflow,

Table 6. Moisture content variation with depths, for different drying systems.

Drying System	Drying Time Weeks	Moisture Content % w.b.				
		Top	Middle	Bottom	Average	Max. Differ.
LT-ST (1979)[1]	0	24.7	23.8	22.7	23.7	1.0*
	1	19.8	20.8	20.7	20.4	1.0*
	2	17.8	18.3	14.1	16.7	4.2
	2	17.0	18.0	14.5	16.5	3.5
	3	15.4	16.4	13.0	14.9	3.4
NA (1979)	3	21.6	19.8	14.7	18.7	6.9
NA (1979)	10	21.5	18.0	15.5	18.3	6.0
LT-ST (1980)	0	22.30	19.25	19.73	20.43	3.05
		18.52	19.13	18.08	18.58	1.05*
	1 (6 days)	18.39	19.02	15.29	17.57	3.73
	1.5 (11 ")	15.54	16.45	14.56	15.52	1.89

*Maximum moisture content difference immediately after stirring

[1]Stirring interval: 48 hrs for 6 hrs in 1979 and 48 hrs for 8 hrs in 1980

Drying conditions: average ambient temperature 4.5°C; Hr 70% in 1979 and 9.4°C, Rh 74% in 1980.

LT-ST: temperature 10°C; Rh 58% (1979)
temperature 14.5°C, Rh 53% (1980)

Table 7. Computer simulation results of natural air (NA), low-temperature-nonstirring (LT-NS), low temperature stirring (LT-ST) and natural air stirring (NA-ST).

Item	NA	LT-NS	LT-ST	NA-ST
Initial MC, 23% w.b.				
MC Top, % w.b.	16.5	16.5	15.5	15.8
MC Middle, % w.b.	15.5	13.4	15.5	15.8
MC Bottom, % w.b.	15.5	12.2	15.4	15.8
Max. MC Difference	1.5	4.3	0.1	0.0
Average MC, % w.b.	15.7	13.9	15.5	15.8
Dry Matter Loss, %	5.4	6.0	2.7	3.3
Drying Time, Hrs.	664	381	272	700
Drying Temperature, °C	4.5	10.0	10.0	4.5
Relative Humidity %	70	58	58	70
Airflow Rate m^3/m^2	7.4	5.92	6.51	8.14

Grain Depth: 3.66m.

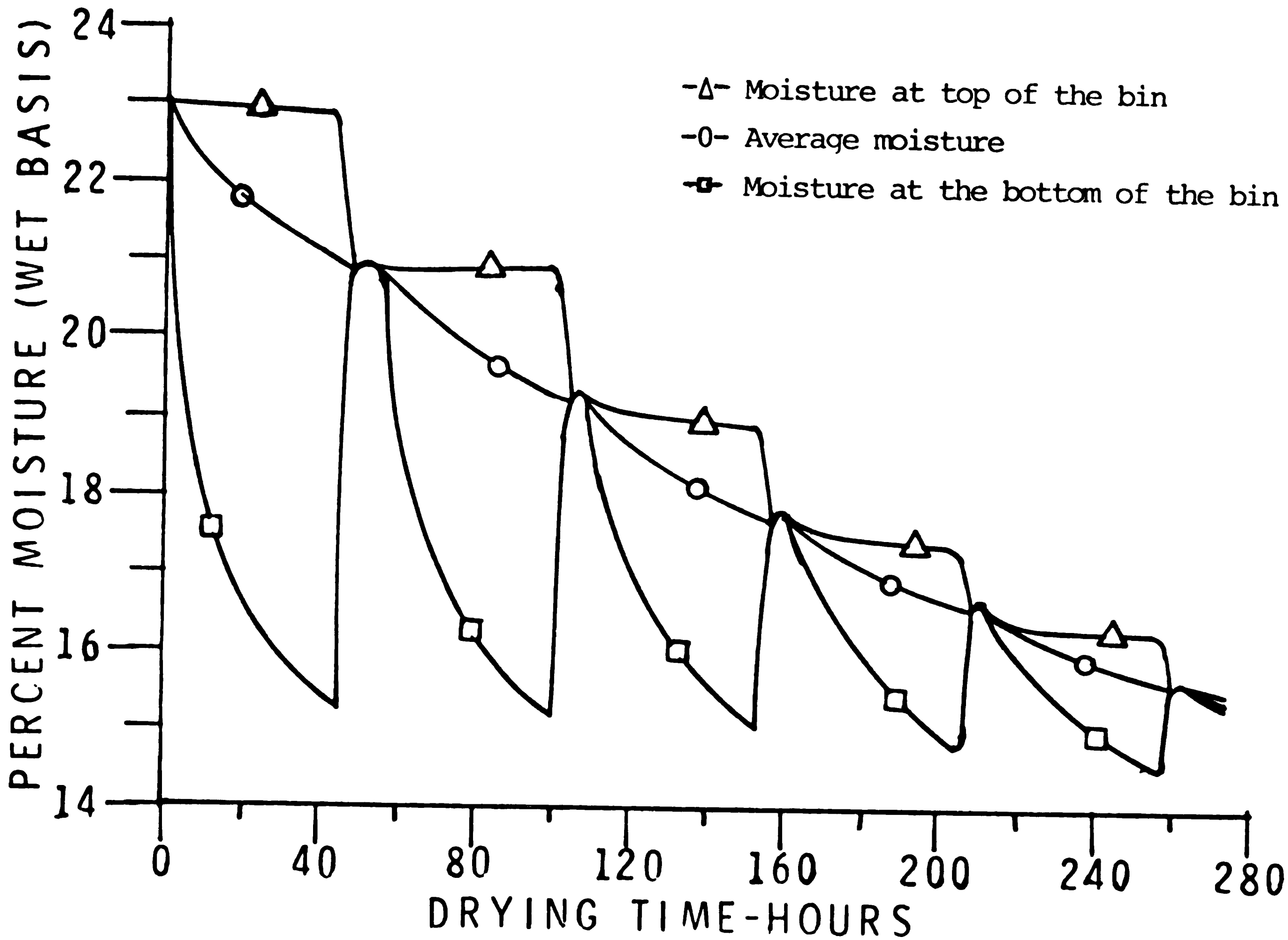
and partly due to the fact that the corn was previously dried in a batch drier and loaded into the LT-ST at about 65°C. The latter procedure resulted in a considerable dryeration effect. Moreover, the corn was stirred eight hours (instead of six hours) every 48 hours.

During stirring the wet corn at the top of the bin is mixed with drier corn at the bottom. It can be seen from Table 6 that corn in the middle of the bin is often wetter than the corn at the bottom and at the top after stirring. However, the maximum difference between the wettest and the driest corn was only about 1.0% immediately after stirring.

The grain along the bin wall was dried to the same moisture content as the corn in the rest of the bin. It was observed that the auger remained against the bin wall during one half of a revolution. The auger did not start rotating around the bin from the same position. The result was complete stirring of the corn at the bin wall and thus complete drying of the corn at the bin wall. Frus (1968) had observed that the corn near the bin wall is not dried if the stirring auger does not travel close to the bin wall.

In low-temperature in-bin drying the bottom layers dry faster than the top layers as the drying front progresses upwards through the bin. Thus, the bottom layer is overdried and the top layer is underdried. The stirring device reduces overdrying of the bottom layer and accelerates drying of the grain at the top of the bin. This can be seen from Figure 7.

In natural air (NA) in-bin drying, overdrying of the bottom layers is not as severe as in low temperature in-bin drying. The relative humidity in NA drying varies with the ambient (no artificial heat is applied). Thus, the equilibrium moisture content is higher, and the drying rate lower than with low electric heat application. Also, overdrying is minimal in natural air in-bin drying (See Tables 6 and 7).



Drying Conditions: Temperature 10°C;
Relative Humidity 40%
Airflow 6.5m^3/m^2
Grain Depth 3.67m

Figure 7. The effect of stirring on in-bin corn drying.

Computer simulations have shown that introduction of a stirring device in a natural air in-bin drying may lower the drying rate, resulting in longer drying time. This is particulary so in poor drying weather conditions (low temperatures and/or high relative humidities).

4.2 Effect of Stirring on Corn Quality

The average quality parameters for the low temperature stir dried and natural air dried corn are tablulated in Table 8. The stir-dried corn is of superior quality than the natural air non stir-dried corn. Stirring ensures uniform corn quality throughout the bin. No hot spots are likely to occur in a stirred bin.

4.2.1 Stress Cracks

The corn to be dried in 1979 in both the stirred and the non-stirred bins was harvested at 34.3% moisture and dried in a high speed, high temperature crossflow continuous dryer to 23.7% for the stirred bin and 24.6% for the natural air bin. The high temperature drying resulted in 41% and 33% heat-stress cracks in the dried corn, respectively. There was a slight reduction (due to sampling error) of the percentage of cracked kernels after low-temperature and natural air drying. This indicates that no heat stresses occurred during the final drying processes. Similar results were observed in the fall of 1980.

4.2.2 Breakage Susceptibility

The high temperature drying increased the breakage susceptibility from 15.7% to 24.9% and 21.6% for stir-dried corn and for natural air dried corn, respectively, in the fall of 1979, and from 16.1 to 33.2% in the fall of 1980. There was no increase in breakage susceptibility in the low-temperature stir dried corn. There was a slight breakage

Table 8. Quality parameters for low temperature stir dried corn and natural air dried corn in 1979 and 1980.

Drying Method	Moisture Content		Stress Cracks	Breakage Susceptibility	BCFM	Viability Percentage		Test Weight
	Initial	Final	%	%	%	Actual	Change	kg/he*
1979								
Undried Corn	34.3	-	0	15.7	0.87	80.5	0	65.4
High Temperature 104°C	34.3	23.7	41	24.86	1.76	49.3	30.7	65.7
LT-ST	23.7	14.9	35	24.77	3.30	51.0	0.0	67.9
NA: High Temp. 104°C	34.3	24.6	33	21.57	1.75	51.3	29.2	66.4
NA	24.6	16.2	29	23.57	2.8	29.0	22.3	66.6
1980								
Undried Corn	29.1	-	0	16.1	0.81	64.2	0	64.2
High Temperature 116°C	29.1	21.8	37	33.2	1.03	15.3	48.9	65.1
LT-ST	21.8	15.5	16	25.2	2.08	8.0	7.3	67.3

* kg per hectoliter

1979 - Breakage susceptibility measured at 12.38% MC

1980 - Breakage susceptibility measured at 9.0% MC

1 Based on $0.07/kWhr electricity, $0.177/liter propane

2, 3, 4 Drying conditions: 1979 - Average ambient temperature 4.5°C; Rh 70%
LT-ST temperature 10.0°C; Rh 58%
1980 - Average ambient temperature 9.4°C; Rh 74%
LT-ST drying temperature 14.5°C; Rh 53%

susceptibility increase in natural air dried corn. The increase may have been caused by mold damage or may be due to sampling error.

4.2.3 Broken Corn and Fine Materials

During the fall of 1979 test the percentage of broken kernels and foreign materials (BCFM) of combine harvested corn was 0.9%. The corn was dried in a continuous flow dryer (Kan-Sun), resulting in 1.8% BCFM. The BCFM increased to 3.3% and 2.8% after drying in the LT-ST and NA systems, respectively. The increase in BCFM is partly caused by the stirring device and partly by the loading and unloading augers. In the fall of 1980 an increase of 1.05% in BCFM was caused by the stirring device. The BCFM was accumulated at the bottom of the LT-ST bin. However, after stirring continuously for 12 hours at the end of drying the BCFM was nearly uniformly distributed throughout the bin.

4.2.4 Viability Change

The viability count as determined by the triphenyltetrazolium chloride color test is given in Table 8. It can be seen that low-temperature stir-drying does not cause any change in the viability of corn. The viability change of 30.7% in the fall 1979 test was caused by drying from 34.3% to 23.7% in the high temperature (104°C) high speed continuous cross-flow dryer. A 56.2% total viability change was observed in 1980 after drying the corn at 116°C in a batch dryer (Farm Fans). The 7.3% change in the LT-ST phase may have been a result of holding the high temperature dried corn at about 70°C in the low-temperature bin for a six-hour tempering period.

Natural air drying in the fall of 1979 resulted in a 22.3% change in viability. This was caused by molding due to the prolonged storage of the corn at a high moisture content, especially at the top of the bin.

4.3 Energy Consumption and Operating Costs

The actual energy consumption and operating costs for the different drying systems are given in Table 9. The standardized energy consumption and operating costs for the same systems are given on Table 10. The standardized parameters are based on combination drying 63.5 tons of corn from 26% wb to 23% in a high temperature dryer and from 23% to 15.5% in the low-temperature and natural air systems; for estimating energy consumption per hectare a yield of 6.9 tons per hectare (100 bu/acre) is assumed. Tables 9 and 10 include the energy consumption and operating costs for high temperature drying of shelled corn from field moisture content to a final moisture content of 15.5%.

The energy costs are expressed in terms of cents per ton of dry corn (15.5% wb) per percentage point of moisture removed. This unit is considered the most meaningful to farmers for the comparison of the different systems.

The energy consumption for low-temperature and natural air systems is very dependent upon the ambient weather conditions. In the fall of 1979, 6061 kWhrs were required to dry 51.74 tons of corn from 23.7% to 14.9% wb in the low-temperature stir-drying (LT-ST) system. The weather conditions during the fall of 1979 were not favorable to drying (the average ambient temperature was 4.5°C and the average ambient relative humidity 70%). In the fall of 1980 the corn matured early and the weather conditions (the average temperature was 9.4°C and the relative humidity 74%) were more favorable to drying. Thus, only 2748 kWhrs were required for drying 46.61 tons from 21.8 to 15.5% moisture content, wet basis. The standardized energy consumption figures are 6340 kWhrs and 4457 kWhrs for 1979 and 1980, respectively.

It can be seen from Tables 9 and 10 that combination drying systems (LT-ST and NA) are less energy consumptive than high temperature drying. The combination drying systems require the least energy input if the corn is harvested at sufficiently low initial moisture contents (e.g. below 23%) to allow direct drying in the low-temperature or natural air systems, without passing through the high temperature phase. Although the drying efficiency of the combination drying systems is better than that of high temperature systems, the combination systems may result in higher energy costs. This is due to the fact that electricity (which is more expensive per kilojoule than propane or natural gas) is the main energy source for these systems, whereas propane (or natural gas) is the principal energy source for the high temperature drying systems. The combination systems would undoubtedly be the least expensive if a cheaper energy source (such as biomass) had been used.

When compared with low-temperature non-stir drying (LT-NS) and natural air (NA) combination drying systems, low-temperature stir combination drying (LT-ST) is less energy comsumptive resulting in lower operating costs. In the fall of 1979, the standardized energy drying efficiencies were 3921 and 3962 kJ/kgH_2O for LT-ST and NA systems, respectively. The energy costs were 80.03 and 80.87 cents per ton per point for the LT-ST and NA systems, respectively (See Table 9).

Silva (1980) compared natural air and low-temperature drying systems at the Kalchik Farms in Bellaire, Michigan in 1978. His results indicate that the energy efficiency of the NA system was about 16% better than the LT-NS system. In terms of energy costs the NA was nearly 30% cheaper than the LT-NS. The fall 1979 test results indicate that the energy efficiency of the LT-ST was about 1% higher and the energy costs about 1% lower, than that of NA drying at the same drying conditions.

Table 9. Actual energy consumption and operating costs (1980 prices)[1] for low-temperature stir drying and natural air drying at the Kalchik Farms, Bellaire, MI.

Drying Method	Moisture Content % wet basis		Corn Quantity tons at 15.5% MC w.b.	Energy Electricity kWhrs	Consumption Propane Liters	Drying Effi-ciency kJ/kg H_2O	Total Energy Equiva-lent Liters/ha	Energy Cost ¢/ton-point	
	In-put	Out-put						Kalchik Farms	Average Michigan Farm
High Temperature Continuous Flow	34.3	23.7	51.74	252	1363	3897	186	45.0	47.2
LT-ST-1979[2]	23.7	14.9	51.74	6061	-	3682	113	57.2	93.2
Combination	34.3	14.9	51.74	6313	1363	3815	299	50.5	68.1
High Temperature Batch Drying	29.1	21.8	46.61	159	1135	5753	171	59.7	62.3
LT-ST -1980[3]	21.8	15.5	46.61	2748	-	2635	57	40.2	65.5
Combination	29.1	15.5	46.61	2907	1135	4443	228	50.7	63.8
High Temperature Continuous Drying (1979)	34.3	24.6	50.65	218	1234	3890	172	45.4	47.6
Natural Air Drying- 1979[4]	24.6	16.2	50.65	5726	-	3622	109	57.9	94.2
Combination	34.3	16.2	50.65	5944	1234	3782	281	51.2	69.2
Automatic Batch	26.0	15.5	7.5	36	310	6584	136	70.1	72.9
Continuous Cross Flow	35.0	13.0	1.46	12	72	4017	348	40.4	42.3

[1] Based on \$0.07/kWhr electricity, \$0.177/liter propane

[2], [3], [4] Drying conditions: 1979 - Average ambient temperature 4.5°C; Rh 70%
LT-ST temperature 10.0°C; Rh 58%
1980 - Average ambient temperature 9.4°C; Rh 74%
LT-ST drying temperature 14.5°C; Rh 53%

Table 10. Standardized energy consumption and operating costs (1980 prices) for low temperature and natural air drying at Kalchik Farms, Bellaire, MI.

Drying Method	Electricity kWh	Electricity kWh/ha	Propane Liters	Propane Liters/ha	Total Energy Equivalent Liters /ha	Energy drying Efficiency kJ/kg H_2O	Drying Cost ¢/ton-point
Low temperature High temperature '79 stir drying combination	6427	698	473	51.4	149	3921	80.03
26-23-15.5% '80	4546	494	635	69.0	138	3633	64.58
High temperature Natural air drying combination 1979	6494	706	478	52.9	150	3962	80.87
High temperature Continuous cross flow dryer '79	249	27	1495	162.4	166	4377	42.30
Automatic batch '79	306	33	2653	288.3	293	7713	73.64
'80	312	34	2224	241.7	246	6488	62.32

Thus, introduction of a stirring device resulted in energy savings in the low-temperature (electrical heat) combination drying system.

The stirring device in the LT-ST bin was operated intermittently every 48 hours for six hours in the fall of 1979, and for 8 hours in 1980. The energy consumption for the stirring device was only 1% and 0.7% of the total energy consumed in 1979 and 1980, respectively. Thus, if periodically operated, the stirring device consumes very little electricity, although resulting in a significant reduction of drying time. The reduced drying time results in reduced energy consumption by the fan and the electric heater in low-temperature systems. Thus, the stirring device reduces operating and energy costs of a low-temperature drying system.

4.4 Capital Budgeting Analysis

The operating costs presented in Tables 9 and 10 do not include labor, maintenance, investment, interest on borrowed money, depreciation, and taxes. To analyze these costs a 381-ton (15,000 bu) drying and storage capacity was designed for the low-temperature non-stir and natural air drying/storage systems. For the LT-ST system, it was assumed that 762 ton of corn can be handled since it is possible to dry two batches per year in this system. This results in reduced investment and other fixed costs per ton of dried corn. With the LT-ST system it is assumed that the farmer dries and sells the first 381 tons of corn at the start of the harvest season and dries the last 381 tons for long term storage on the farm.

The cost estimates and assumptions are summarized in Table 11. The costs were estimated according to the procedure outlined in Appendix A and were used in a capital investment computer model (TELPLAN) designed by Harsh (1978).

The economic analysis results (Table 12) indicate that for drying 381 tons of corn annually, the total drying costs are nearly the same for the three systems analyzed (LT-NS, LT-ST and NA). The total drying costs are \$19.74, \$21.00 and \$21.32 per ton for the NA, LT-ST and LT-NS respectively. The drying and investment cost per ton can be reduced in the LT-ST system by drying two batches per year. The total cost for drying 762 tons per year in the LT-St is \$15.23 per ton, assuming that the first 381 tons is sold. (See Table 12). It may be necessary to store all the corn dried on the farm. For 762 ton annual capacity six 381-ton extra bins are required for storage. Due to the extra investment, the total drying costs are \$17.13 and \$17.15 per ton for the LT-ST and NA systems, respectively. Thus, for 762-ton annuall capacity the drying costs are nearly equal for the two systems. However, the total drying costs for the NA system increase faster (than for LT-ST system) with increasing capacity because a drying fan is installed in each of the NA bins. In the LT-ST system stirrers, drying fans, and heaters are not required in all the bins. Thus, the LT-ST system requires less investment costs than the NA system for capacities greater than 762 tons annually. However, the actual relative investment costs depend on the system design.

Thus, the LT-ST is the least expensive for drying capacities greater than 380 tons annually. Considering the superior grain quality after LT-ST drying, the LT-ST is a better drying system than either the NA or LT-NS system.

Table 11. Estimates/Assumptions for a 10 year budgeting analysis (1980 prices)[1].

Parameter Estimated	Drying Combination Systems: Low temp with stir	Low temp without stir	Natural air
Annual quantity, ton[2]	762	381	381
Total Investment, $	45032	38286	38274
Salvage value of investment, %	10	10	10
Annual interest rate on loan, %	12	12	12
Energy costs[3], $/ton point and $/ton	0.72 7.56	0.80 8.40	0.73 7.67
Labor costs, $/ton	0.95	0.84	0.84
Maintenance, $ for 10 yrs.	750	500	400

[1]See Appendix A

[2]It is assumed that corn will be harvested at 26% w.b., dried to 23% in a high temperature drier and dried to 15.5% in the final phase.

[3]Based on $0.07/kWhr electricity, $0.177/liter propane.

Table 12. Economic analysis results for three high temperature-low temperature combination drying/storage systems for Michigan (1980 prices)[1].

System (381 tons annually) from 26-23-15.5% w.b.	[2]Annual Cost in $ per ton per percentage point removal			Initial Capital Investment per ton, $
	Fixed Cost, $	Variable Cost, $	Total Cost, $	
Low-temperature stir drying	1.19 (12.50)[3]	.81 (8.51)	2.00 (21.00)	118.19
Low-temperature stir drying (762 tons)[4]	0.64 (6.72)	0.81 (8.51	1.45 (15.23)	59.10
Low-temperature without stirring	1.15 (12.08)	0.88 (9.24)	2.03 (21.32)	100.49
Natural air (without stirring)	1.07 (11.24)	0.81 (8.51)	1.88 (19.74)	100.46

[1] See Appendix B and C for input and detailed analyses respectively.

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

[3] Figures in brackets are the equivalent cost, $/ton.

[4] Low-temperature stir-drying system can dry twice as much as other systems per year.

5. CONCLUSIONS

1. The LT-ST drying reduces the total drying time from over 10 weeks in a NA system to less than 3 weeks, depending on the weather conditions.
2. When compared with high temperature dryers, the LT-ST is a more energy efficient system and results in about 30% energy savings. However, like most other combination systems, it is more expensive to run than the high temperature dryers since electricity, which is more expensive per kilojoule than propane, is its main source of energy.
3. The combination systems studied require nearly the same operating costs per unit, if 380 tons of corn are dried per year. However, the LT-ST system would be about 40% cheaper if twice as much corn is dried per year without on-the-farm storage.
4. If on-the-farm storage is required, the total drying costs increases faster with increasing capacity for the NA than for the LT-ST since a greater investment is required for the NA system.
5. LT-ST drying results in high, uniform quality corn. "Hot spots" and overdried corn are reduced. Thus, the LT-ST is a more reliable drying system than either the NA or LT-NS systems.

6. SUGGESTIONS FOR FUTURE WORK

As a result of this study, the following suggestions are made for further investigation:

1. To study the effect of stirring on energy costs if biomass or solar energy rather than electric heat is used as fuel for low-temperature drying.
2. To compare, side by side, continuous stirring with intermittent stirring.
3. Perform an optimization study to determine the optimum relative energy input for the fan, heater and the stirrer for corn drying from different initial moisture contents to 15.5% MC, wb.
4. Research should be done in tropical Africa, particularly in Kenya to study the technical and economic feasibility of low-temperature stir-drying of cereal grains using solar energy or biomass as source of heat.

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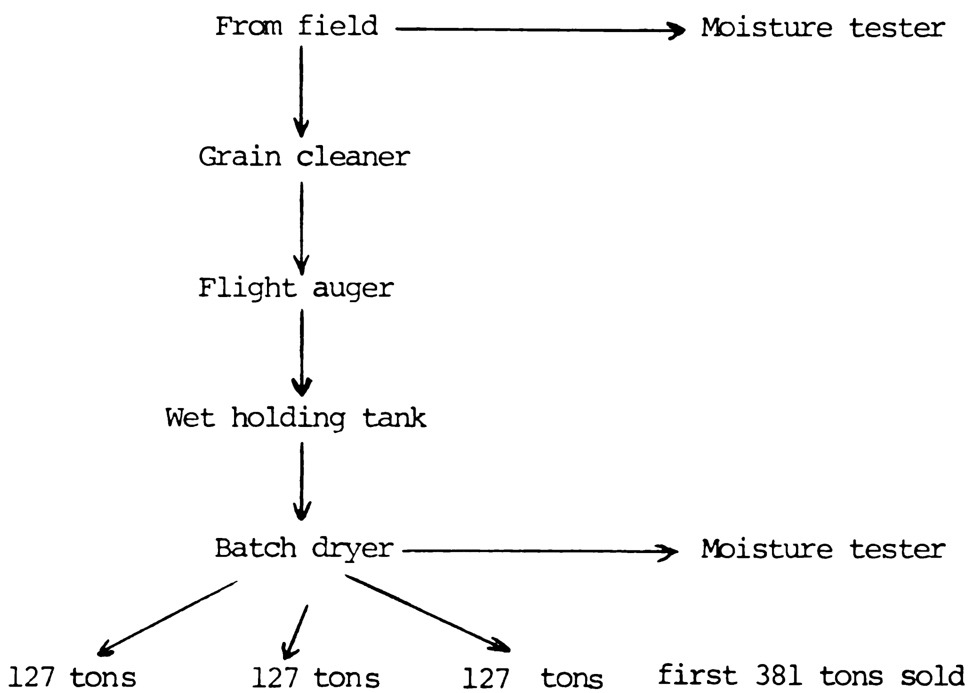
8. APPENDICES

APPENDIX A

INVESTMENT COST ESTIMATES

A1. Batch-Low Temperature Stir Combination Drying (762 tons)

1. System operation



Initial moisture content 26% (from field)

Intermediate moisture content 23% (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	Stirring devices	4,860.00
3	Extra rings	1,800.00
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	47,277.00
	Less 10% discount	42,549.00
	Installation	1,600.00
	Miscellaneous (2% total investment)	883.00
	TOTAL COST OF THE SYSTEM	$45,032.00

3. Estimated salvage value at the end of 10 years

Bins	$ 5,893.00
Stirrers	3,000.00
Perforated floor	2,332.00
Electrical	500.00
Concrete	1,260.00
Miscellaneous	365.00
Installation	500.00
TOTAL	$13,850.00

at 35% salvage cost = $4,847.00

% salvage value total investment = $5,425.00 ÷ $45,032.00 ≈ 10%.

4. Estimated annual rate of interest on loan: 12% per year

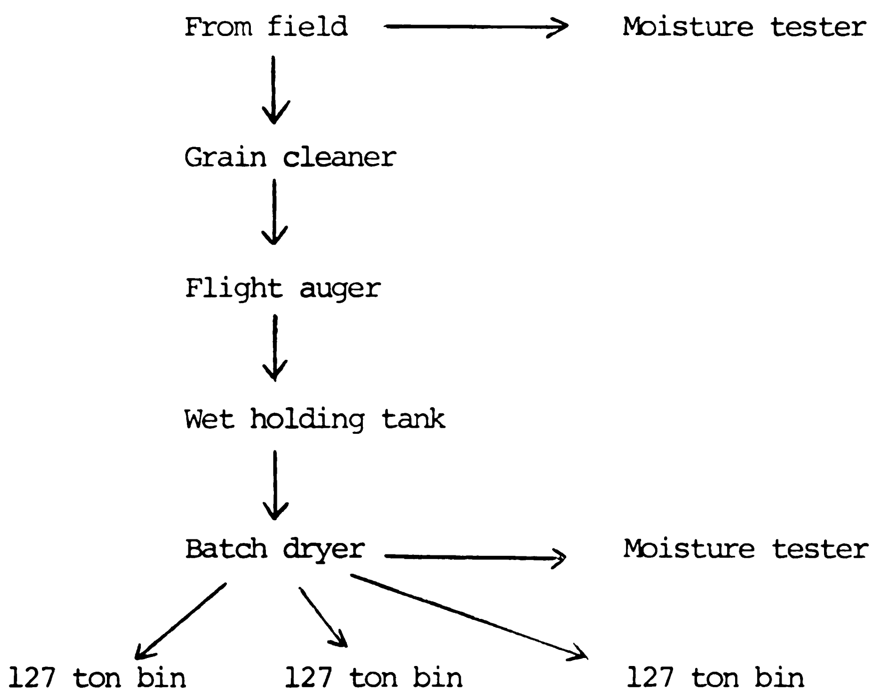
5. Estimated direct energy cost: $0.72 per ton per point

6. Estimated labor cost: $0.09/ton

7. Estimated maintenance cost: $750.00

A2. Batch-Low Temperature Combination Drying (381 tons)

1. System operation



Initial moisture content 26% (from field)

Intermediate moisture content 23% (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 = $3,797.00

% salvage value total investment = $3,797.00 ÷ $38.286.00 ≈ 10%.

4. Estimated annual rate of interest on loan

   12% per year

5. Estimated direct energy cost

   $0.80 per point per ton

6. Estimated labor cost

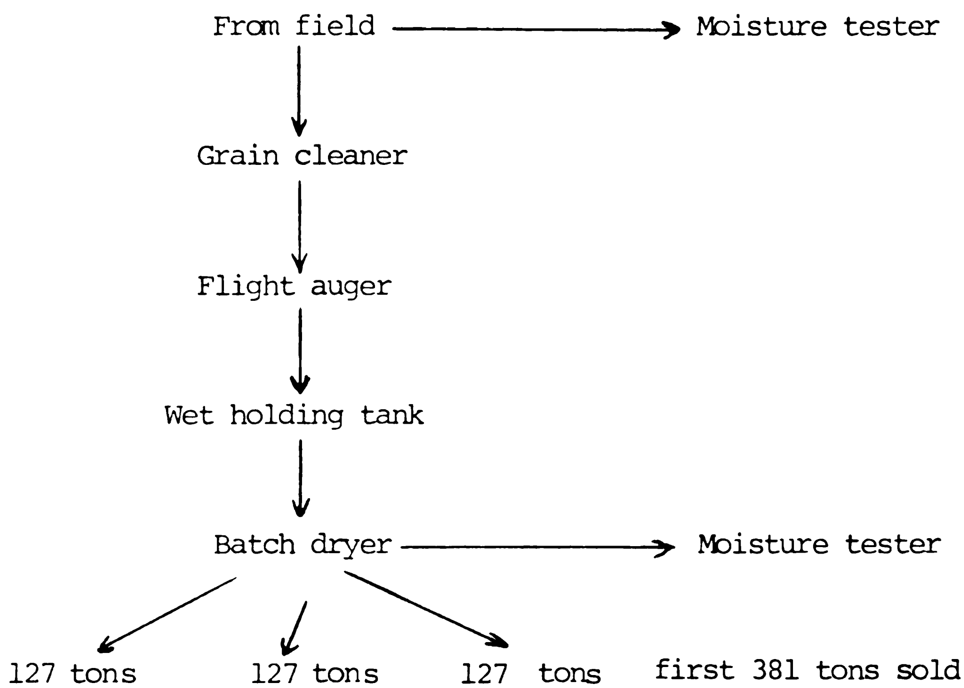
   $0.08 per point per ton

7. Estimated maintenance cost

   $500 in 10 years

A1. Batch-Low Temperature Stir Combination Drying (762 tons)

1. System operation



Initial moisture content 26% (from field)

Intermediate moisture content 23% (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	Stirring devices	4,860.00
3	Extra rings	1,800.00
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	47,277.00
	Less 10% discount	42,549.00
	Installation	1,600.00
	Miscellaneous (2% total investment)	883.00
	TOTAL COST OF THE SYSTEM	$45,032.00

3. Estimated salvage value at the end of 10 years

Bins	$ 5,893.00
Stirrers	3,000.00
Perforated floor	2,332.00
Electrical	500.00
Concrete	1,260.00
Miscellaneous	365.00
Installation	500.00
TOTAL	$13,850.00

at 35% salvage cost = $4,847.00

% salvage value total investment = $5,425.00 ÷ $45,032.00 ≈ 10%.

4. Estimated annual rate of interest on loan: 12% per year

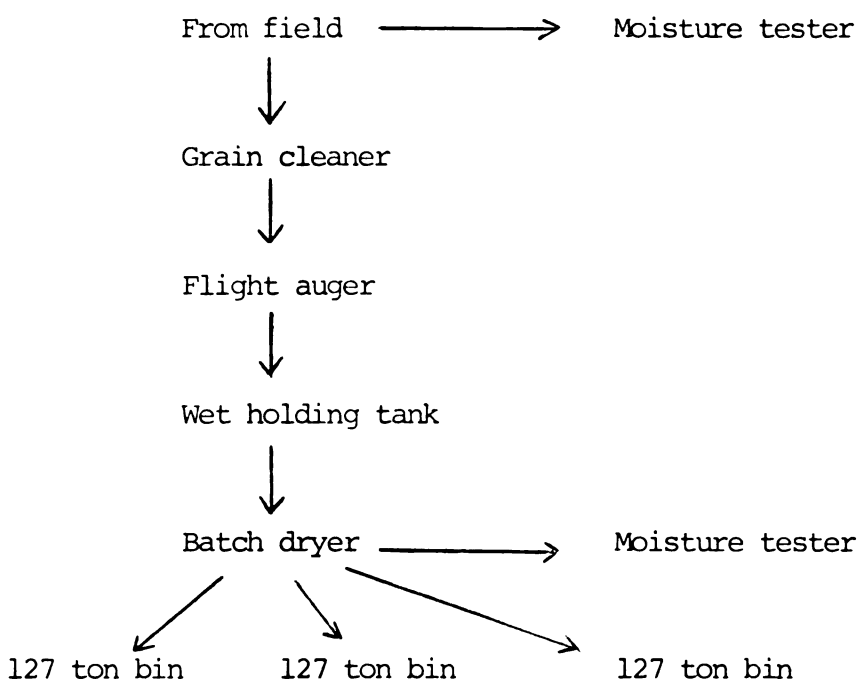
5. Estimated direct energy cost: $0.72 per ton per point

6. Estimated labor cost: $0.09/ton

7. Estimated maintenance cost: $750.00

A2. Batch-Low Temperature Combination Drying (381 tons)

1. System operation



Initial moisture content 26% (from field)

Intermediate moisture content 23% (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 = $3,797.00

% salvage value total investment = $3,797.00 ÷ $38.286.00 ≈ 10%.

4. Estimated annual rate of interest on loan

   12% per year

5. Estimated direct energy cost

   $0.80 per point per ton

6. Estimated labor cost

   $0.08 per point per ton

7. Estimated maintenance cost

   $500 in 10 years

APPENDIX B

RESULTS OF CAPITAL INVESTMENT ANALYSIS

USING A TELPLAN PROGRAM

APPENDIX B3

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

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

NAME LOW-TEMPERATURE NON-STIR DRYING (381 tons p.a.) ADDRESS ______

Problem: To evaluate the investment of capital to reduce or eliminate costs including custom hire & 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 ($)	01. 002.03	______
2a.	Cost savings (or income produced) per unit* for a second class of expenses (or income). For example, additional per unit annual losses associated with custom hire ($)	02. 000.00	______
3a.	Normal number of units* per year on which costs will be reduced (or income generated).	03. 004000 | _ _ _	______
b.	Percent of units* indicated in Line 3a that will be absorbed by investment in the year of purchase.		

Section II. Investment Information.

		LINE NO.	ADJUSTED ANALYSIS
4a.	Total dollar cost including undepreciated balance of trade-in items.	04. 038286 | 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. 038286 | 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).

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

		LINE NO.	ADJUSTED ANALYSIS
6a.	*Depreciation years*	06. 10 | 10 | 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 | 12.0	
b.	*Repayment period of loan-years*		
c.	*Annual rate of interest on loan(%)*		
8a.	*Per hour^x fuel cost of operating investment** ($)*	08. 00.72 | 00.00	
b.	*Per hour^x fuel cost of operating associated equipment** ($)*		
9a.	*Per hour^x labor cost of operating investment & associated equipment.*	09. 00.09 | 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. 00750	
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. |3 0|3 0|3 0|	
b.	Tax bracket for first 1/2 years of investment.		
c.	Tax bracket for last 1/2 years of investment.		
13a.	Desired percentage rate of return on investment for first 1/2 years of investment.	13. |1 5|1 5|0 0 0 .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 Assumptions[xx]

Enter "O" on line following last modification to be made. If none, enter "O" on line 14)

14a. / b.	Assumption value desired / Assumption code	14. |0 1 . 0|0 1|	
15a. / b.	Assumption value desired / Assumption code	15. |0 6 . 0|0 2|	
16a. / b.	Assumption value desired / Assumption code	16. |0 8 . 0|0 5|	
17a. / b.	Assumption value desired / Assumption code	17. |0 6 . 0|0 8|	
18a. / b.	Assumption value desired / Assumption code	18. |0 1 . 0|0 9|	
19a. / b.	Assumption value desired / Assumption code	19. |0 1 . 6|1 0|	
20a. / b.	Assumption value desired / Assumption code	20. |0 6 . 0|0 3|	

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

APPENDIX B2

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

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

NAME LOW-TEMPERATURE STIR DRYING (381 tons p.a.) ADDRESS

Problem: To evaluate the investment of capital to reduce or eliminate costs including custom hire & 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. 002.00

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. 000.11

3a. Normal number of units* per year on which costs will be reduced (or income generated). — 03. 004000 | 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. 045032 | 10

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. 045032 | 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).

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

		LINE NO.	ADJUSTED ANALYSIS
6a.	Depreciation years	06. |10|10|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|12.0|	
b.	Repayment period of loan-years		
c.	Annual rate of interest on loan(%)		
8a.	Per hour[x] fuel cost of operating investment** ($)	08. |00.72|00.00|	
b.	Per hour[x] fuel cost of operating associated equipment** ($)		
9a.	Per hour[x] labor cost of operating investment & associated equipment.	09. |00.09|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. |00750|	
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. 3 0 | 3 0 | 3 0	
b.	Tax bracket for first 1/2 years of investment.		
c.	Tax bracket for last 1/2 years of investment.		
13a.	Desired percentage rate of return on investment for first 1/2 years of investment.	13. 1 5 | 1 5 | 0 0 0 . 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 Assumptions[xx]

Enter "O" on line following last modification to be made. If none, enter "O" on line 14)

		LINE NO.	ADJUSTED ANALYSIS
14a.	Assumption value desired	14. 0 1 . 0 | 0 1	
b.	Assumption code		
15a.	Assumption value desired	15. 0 6 . 0 | 0 2	
b.	Assumption code		
16a.	Assumption value desired	16. 0 8 . 0 | 0 5	
b.	Assumption code		
17a.	Assumption value desired	17. 0 6 . 0 | 0 8	
b.	Assumption code		
18a.	Assumption value desired	18. 0 1 . 0 | 0 9	
b.	Assumption code		
19a.	Assumption value desired	19. 0 1 . 6 | 1 0	
b.	Assumption code		
20a.	Assumption value desired	20. 0 6 . 0 | 0 3	
b.	Assumption code		

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

APPENDIX B3

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

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

NAME LOW-TEMPERATURE NON-STIR DRYING (381 tons p.a.) *ADDRESS* ______

Problem: To evaluate the investment of capital to reduce or eliminate costs including custom hire & 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 ($)*	01. 0 0 2 . 0 3	______
2a.	*Cost savings (or income produced) per unit* for a second class of expenses (or income). For example, additional per unit annual losses associated with custom hire ($)*	02. 0 0 0 . 0 0	______
3a.	*Normal number of units* per year on which costs will be reduced (or income generated).*	03. 0 0 4 0 0 0 - - -	______
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. 0 3 8 2 8 6 0 0	______
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. 0 3 8 2 8 6 1 0	______
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).*

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

		LINE NO.	ADJUSTED ANALYSIS
6a.	*Depreciation years*	06. |10|10|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|12.0|	
b.	*Repayment period of loan-years*		
c.	*Annual rate of interest on loan(%)*		
8a.	*Per hour*[x] *fuel cost of operating investment*** *($)*	08. |00.80|00.00|	
b.	*Per hour*[x] *fuel cost of operating associated equipment*** *($)*		
9a.	*Per hour*[x] *labor cost of operating investment & associated equipment.*	09. |00.08|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. |00500|	
11a.	*Number of units* handled per hour*[x]	11. |0001.00|	

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* *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. 3 0 | 3 0 | 3 0	
b.	Tax bracket for first 1/2 years of investment.		
c.	Tax bracket for last 1/2 years of investment.		
13a.	Desired percentage rate of return on investment for first 1/2 years of investment.	13. 1 5 | 1 5 | 0 0 0 . 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 Assumptions[xx]

Enter "O" on line following last modification to be made. If none, enter "O" on line 14)

		LINE NO.	ADJUSTED ANALYSIS
14a.	Assumption value desired	14. 0 1 . 0 | 0 1	
b.	Assumption code		
15a.	Assumption value desired	15. 0 6 . 0 | 0 2	
b.	Assumption code		
16a.	Assumption value desired	16. 0 8 . 0 | 0 5	
b.	Assumption code		
17a.	Assumption value desired	17. 0 6 . 0 | 0 8	
b.	Assumption code		
18a.	Assumption value desired	18. 0 1 . 0 | 0 9	
b.	Assumption code		
19a.	Assumption value desired	19. 0 1 . 6 | 1 0	
b.	Assumption code		
20a.	Assumption value desired	20. 0 6 . 0 | 0 3	
b.	Assumption code		

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

	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.		
13a. Desired percentage rate of return on investment for first 1/2 years of investment.	13. |15|15|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 Assumptions[xx]

Enter "O" on line following last modification to be made. If none, enter "O" 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.

		LINE NO.	ADJUSTED ANALYSIS
6a.	Depreciation years	06. |10|10|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|12.0|	
b.	Repayment period of loan-years		
c.	Annual rate of interest on loan(%)		
8a.	Per hour[x] fuel cost of operating investment** ($)	08. |00.73|00.00|	
b.	Per hour[x] fuel cost of operating associated equipment** ($)		
9a.	Per hour[x] labor cost of operating investment & associated equipment.	09. |00.08|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. |00400|	
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.		
13a. Desired percentage rate of return on investment for first 1/2 years of investment.	13. 15 15 000 .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 Assumptions[xx]		
Enter "O" on line following last modification to be made. If none, enter "O" 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 C

GENERAL ECONOMIC ANALYSIS
FOR A 10-YEAR PERIOD FOR THREE
CORN DRYING SYSTEMS

Appendix Cl. General economic analysis for a 10 year period for the LT-ST drying system (381 tons annually).

Yr	Total Returns	Deprec-iation	Princ + Int.	Repairs	Fuel + Lub.	Labor	Sup-plies	After-TX Cash flow
1	8946	7417	3774	31	3577	382	0	6276
2	9483	7517	8492	53	3863	404	0	-1858
3	10052	6013	8492	68	4172	429	0	-2147
4	10655	4811	8492	81	4506	454	0	-2390
5	11294	3849	8492	93	4866	482	0	-2598
6	11972	3079	8492	105	5256	511	0	-2784
7	12690	2463	8492	117	5676	541	0	-2956
8	13452	1970	8492	128	6130	574	0	-3125
9	14259	1576	5284	140	6621	608	0	80
10	15114	1261	0	153	7150	645	0	5317
Totals								
	117917	39956	68502	969	51817	5030	0	-6185

1. Economic savings (discounted dollars) over period of use if investment is made = $ -26.
2. Number of units on which analysis was made = 4000. (381 tons @ 10.5 MC percentage points removed)
3. Depreciation method used in analysis = 4.
4. Annual non-discounted returns, selected costs and cash flows.

Appendix C2 General economic analysis for a 10 year period for the LT-ST drying system (762 tons annually).

Yr	Total Returns	Deprec-iation	Princ + Int.	Repairs	Fuel + Lub.	Labor	Sup-plies	After-TX Cash flow
1	13228	7417	3774	31	7154	733	0	6502
2	14022	7517	8492	53	7726	809	0	-1668
3	14863	6013	8492	68	8344	858	0	-2000
4	15755	4811	8492	81	9012	909	0	-2292
5	16700	3849	8492	93	9733	934	0	-2557
6	17703	3079	8492	105	10511	1021	0	-2809
7	18765	2463	8492	117	11352	1083	0	-3056
8	19891	1970	8492	128	12261	1148	0	-3310
9	21084	1576	5284	140	13241	1216	0	-201
10	22349	1261	0	153	14301	1289	0	4925
Totals								
	174360	39956	68502	969	103635	10060	0	-6466

1. Economic savings (discounted dollars) over period of use if investment is made = $ 202.
2. Number of units on which analysis was made = 8000. (762 tons @ 10.5 MC percentage points removed)
3. Depreciation method used in analysis = 4.
4. Annual non-discounted returns, selected costs and cash flows.

Appendix C3 General economic analysis for a 10 year period for the LT-ST drying system (381 tons annually).

Yr	Total Returns	Deprec- iation	Princ + Int.	Repairs	Fuel + Lub.	Labor	Sup- plies	After-TX Cash flow
1	8607	6857	3211	21	3974	339	0	5542
2	9123	6286	7225	35	4292	360	0	-1583
3	9671	5029	7225	45	4636	381	0	-1833
4	10251	4023	7225	54	5007	404	0	-2047
5	10866	3218	7225	62	5407	428	0	-2235
6	11518	2575	7225	70	5840	454	0	-2407
7	12209	2060	7225	78	6307	481	0	-2571
8	12941	1648	7225	86	6811	510	0	-2735
9	13718	1318	4496	94	7356	541	0	-31
10	14541	1055	0	102	7945	573	0	4395
Totals								
	113445	34069	58282	647	57575	4471	0	-5505

1. Economic savings (discounted dollars) over period of use if investment is made = $ 6.
2. Number of units on which analysis was made = 4000. (381 tons @ 10.5 MC percentage points removed)
3. Depreciation method used in analysis = 4.
4. Annual non-discounted returns, selected costs and cash flows.

Appendix C1. General economic analysis for a 10 year period for the LT-ST drying system (381 tons annually).

Yr	Total Returns	Deprec- iation	Princ + Int.	Repairs	Fuel + Lub.	Labor	Sup- plies	After-TX Cash flow
1	8946	7417	3774	31	3577	382	0	6276
2	9483	7517	8492	53	3863	404	0	-1858
3	10052	6013	8492	68	4172	429	0	-2147
4	10655	4811	8492	81	4506	454	0	-2390
5	11294	3849	8492	93	4866	482	0	-2598
6	11972	3079	8492	105	5256	511	0	-2784
7	12690	2463	8492	117	5676	541	0	-2956
8	13452	1970	8492	128	6130	574	0	-3125
9	14259	1576	5284	140	6621	608	0	80
10	15114	1261	0	153	7150	645	0	5317
Totals	117917	39956	68502	969	51817	5030	0	-6185

1. Economic savings (discounted dollars) over period of use if investment is made = $ -26.
2. Number of units on which analysis was made = 4000. (381 tons @ 10.5 MC percentage points removed)
3. Depreciation method used in analysis = 4.
4. Annual non-discounted returns, selected costs and cash flows.

APPENDIX D

COMPUTER LISTING OF THE PROGRAM "FIXED" USED TO SIMULATE CORN DRYING IN A FIXED BED

APPENDIX D

```
      PROGRAM FIXED (INPUT,OUTPUT,TAPE60=INPUT,TAPE61=OUTPUT,TAPE1)
C*
C*        M I C H I G A N   S T A T E   U N I V E R S I T Y
C* A G R I C U L T U R A L   E N G I N E E R I N G   D E P A R T M E N T
C*       F I X E D   B E D   G R A I N   D R Y E R   M O D E L
C*                 F.W. BAKKER-ARKEMA, PROJECT LEADER
C*                        M. G. ROTH, PROGRAMMER
C*                        E.W.RUGUMAYO , MODIFIER
C*            ELIUD N. MWAURA,MODIFIER TO SIMULATE STIR DRYING
C*
C*    DESCRIPTION
C*         MAIN PROGRAM FOR THE SIMULATION OF A FIXED BED DRYER
C*
C*    SUBROUTINES USED
C*         BLOCKDATA
C*         LAYEQ
C*         READYTH
C*         ZEROIN
C*
C*    FUNCTION SUBPROGRAMS USED
C*         SYCHART PACKAGE
C*         EMC
C*         SOLVE
C*
      COMMON /MAIN/ XMT,THT,RHT,DELT,CMM,XMO,IAB,TIME
      COMMON /PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
      COMMON /PRESS/PATM
      COMMON /NAME/INAME,IPROD,NEQ,NEQ1
      COMMON /ARRAYS/ T(51,2),H(51,2),XM(51),RH(51)
      COMMON /CONS/ CON1,CON2,CON3,CON4,CON5,CON6,CON7,CON12,CON13
      COMMON /FLAGS/ JX,JM,ICON
      DIMENSION XMEPR(51),DM(51),TEQ(51),DEEP(21),WB(51),INAME(3)
      EXTERNAL SOLVE
C*    DEFINE EQUILIBRIUM RH FUNCTION (THOMPSON, 1972)
      ERH(T,XM) = 1. - EXP(- .382*(1.8*T + 82.)*XM**2)
      DATA RHC,D,PRT,TIME,ITERCT,IEXIT,JK,KCON,KAB/.9999999999,3*.0,5*0/
      DATA IAB/0/
      F(T) = T + 273.16
      PRTT = 0.0
C*    INPUT CONDITIONS OF DRYER TO BE SIMULATED
      READ 150,XMO,THIN,CMM,DEPTH,INDPR,NLPF,TT,TBTPR,DELT,NEQ
      CFM = 3.2807*CMM
      DEPTHF = 3.2807*DEPTH
      HP=DEPTHF*(CFM**1.944)*3.0792E-6
      HPHOUR=HP*TT
      BTUAIR=HPHOUR/3.929E-4
      ENJAIR = 1055.1*BTUAIR
C*    COMPUTE STEP SIZE, NUMBER OF NODES AND DEPTH BETWEEN PRINTS
      DELX=1./NLPF
      IND=NLPF*DEPTH
      IND1=IND+1
      DBTPR=INDPR*DELX
C*    COMPUTE OUTPUT DEPTHS FOR PRINTING
      DO 100 I=1,IND1,INDPR
      JK=JK+1
      DEEP(JK)=D
      D=D+DBTPR
  100 CONTINUE
```

APPENDIX D - Continued

```
C*   COMPUTE EQUILIBRIUM RH AND INITIALIZE ARRAYS
      RHIN=0.9*ERH(THIN,XMO)
      HINIT=HADBRH(F(THIN),RHIN)
      DO 101 I=1,IND1
      XM(I)=XMO
      TEQ(I)=0.0
      H(I,1)=HINIT $ T(I,1)=THIN $ RH(I)=RHIN
  101 CONTINUE
      HIN = HINIT
C*   CONVERT AIRFLOW TO KG/HR AND COMPUTE CONVECTIVE HEAT TRANSFER
C*   COEFFICIENT AND EQUILIBRIUM MOISTURE CONTENT
      GA=60.*CMM/VSDBHA(F(THIN),HIN)
      IF(GA - 2441.214) 2,1,1
    1 HC = 2909.458839*GA**.59
      GO TO 3
    2 HC = 6480.645534*GA**.49
    3 CONTINUE
C*   PRINT HEADER PAGE OF CONDITIONS AND PROPERTIES
      PRINT 210,INAME,IPROD,THIN,XMO,CMM,GA,CA,CP,CV,CW
     1,HC,PATM,HFG,RHOP,SA,DEPTH,DELX,DBTPR,TT,TBTPR,ENJAIR
      PRINT 218,DELT
C*   PRINT DEPTHS FOR WHICH LATER OUTPUT CORRESPONDS
      PRINT 211,(DEEP(I),I=1,JK)
C*   COMPUTE CONSTANTS USED BY EQUATIONS WITHIN LOOP
      CON1=GA*DELT
      CON2=CW-CV
      CON12=CON1*CON2
      CON3 = HFG + 117.86*(CW-CV)
      CON13=CON1*CON3
      CON4=RHOP*DELX
      CON5=CON4/CON1
      CON6=CON1/CON4
C*   COUNT NUMBER OF STIRRINGS
      TSTIR=0.
      KEYTIME=0
      KEY2=0
C*   BEGIN TIME LOOP
    4 TIME=TIME+DELT
      KEYTIME=KEYTIME+DELT
       KEY1=0
       IF(NEQ.EQ.4) GO TO 300
C*    CHECK IF TIME TO READ NEW DATA INPUT
       IF(TIME-PRT) 6,5,5
  300 CONTINUE
C*    READ RECORDED GRAIN TEMP.THINC,INPUT DRYING TEMP.TIN AND
C*    ABSOLUTE HUMIDITY, HIN
    5    TIN=10.  $  HIN=.003
       KEY1=1
       NEQ1 = NEQ
       V1 = T(1,1) $ V2 = XM(1) $ V3 = H(1,1) $ V4 = RH(1)
     8 H(1,2)=HIN
       T(1,2)=TIN
       RH(1) = RHDBHA(F(T(1,2)),H(1,2))
    6    CONTINUE
C*    CHECK IF STIRRING CONDITIONS HAVE BEEN MET
C*   IF SO SET ALL PROPERTIES EQUAL TO AVERAGE CONDITIONS
       IF(KEYTIME .GE. 48)GOTO 50
       GOTO 55
    50  CONTINUE
```

APPENDIX D - Continued

```
      DO 120 J=1,IND1
      XM(J)=XMAVE
      T(J,1)=TAVE
      H(J,1)=HAVE
  120  CONTINUE
      TSTIR=TSTIR+1.
      KEY2=KEY2+1
      IF(KEY2 .GT. 1)GOTO 245
      PRINT 230,TIME
  230  FORMAT(*0*,*STIRRING OCCURRED AT *,F6.2,* HRS*)
  245  CONTINUE
      IF(KEY2 .LT. 6)GOTO 243
      KEY2=0
      KEYTIME=0
  243  IF(KEY1-1)244,55,55
  244  H(1,2)=HAVE
      T(1,2)=TAVE
      RH(1)=RHDBHA(F(T(1,2)),H(1,2))
      V1 = T(1,1) $ V2 = XM(1) $ V3 = H(1,1) $ V4 = RH(1)
  55    CONTINUE
      KEY1=0
C*   EVALUATE THIN LAYER DRYING EQUATION AT AIR INLET
      THT=T(1,1) $ XMT=XM(1) $ RHT=RHDBHA(F(THT),H(1,1))
      CALL LAYEQ
      XM(1)=XMT
C*   BEGIN DEPTH LOOP
      DO 102 J=2,IND1
      JX = J
      JM=J-1
C*   USE PREVIOUS VALUE OF H FOR INITIAL GUESS
      HJ2=H(JM,2)
C*   CALL SOLVE TO COMPUTE TRIAL T, XM, H, RH
      DIFF=SOLVE(HJ2)
C*   CHECK CONDENSATION FLAG
      IF(ICON) 31,31,30
   30 KCON=KCON+1
      GO TO 43
C*   SET LIMITS ON H
   31 IF(DIFF) 36,43,32
C*   SOLVING FOR ABSORPTION CONDITIONS
   32 HLOW=.5*ERH(THT,XMT)
C*   CHECK FOR FEASIBLE HLOW
   33 IF(XMT-EMC(HLOW,THT)) 34,35,35
C*'***    DECREASE HLOW UNTIL XM .GT. EMC
   34 HLOW=.5*HLOW
      GO TO 33
   35 HLOW=HADBRH(F(THT),HLOW)
      HHI=H(J,2)
      KAB=KAB+1
      GO TO 42
C*   SOLVING FOR DRYING CONDITIONS
   36 HLOW=H(J,2)
C*   CHECK FOR SUPERSATURATED GRAIN
      IF(XMT-EMC(RHC,THT)) 38,37,37
   37 HHI=HADBRH(F(THT),RHC)
      GO TO 42
   38 HHI=.5*(1.+ERH(THT,XMT))
C*   CHECK FOR FEASIBLE HHI
   39 IF(EMC(HHI,THT)-XMT) 40,41,41
C*   INCREASE HHI UNTIL EMC .GT. XM
   40 HHI=.5*(1.+HHI)
```

APPENDIX D - Continued

```
      GO TO 39
   41 HHI=HADBRH(F(THT),HHI)
C*
C*    INITIATE SEARCH FOR H, T, XM
C*
   42 CALL ZEROIN(HLOW,HHI,.0001,SOLVE)
   43 XM(J)=XMT
C*    END DEPTH LOOP
  102 CONTINUE
      XMAVE=0. $ DMAVE=0. $ WBAVE=0.
      TAVE = 0.0
      HAVE=0
      DO 103 J=1,IND1
      JX = J
C*    SHIFT ARRAYS
      T(J,1)=T(J,2)
      H(J,1)=H(J,2)
C*    COMPUTE EQUILIBRIUM MOISTURE CONTENT
      XMEFR(J)=EMC(RH(J),T(J,2 ))
C*    SUM MOISTURE CONTENTS
      XMAVE=XMAVE+XM(J)
C*    CALCULATE DRY MATTER DECOMPOSITION (THOMPSON, 1972)
      XMDB=100.*XM(J) $ XMWB=XMDB/(1.+XM(J)) $ TJ=T(J,1)
      WB(J)=.01*XMWB $ WBAVE=WBAVE+WB(J)
C*    COMPUTE TEMPERATURE MULTIPLIER FOR EQUIVALENT TIME
      IF(TJ-15.5) 21,22,22
C*    T.LT.15.5DEG C
   21 AMT = 128.76*EXP(-4.68*((1.8*TJ + 32.)/60.))
      GO TO 26
C*    (T.GE.15.5DEG C) AND (XM.LE.19WB)
   22 AMT = 32.3*EXP(-3.48*((1.8*TJ + 32.)/60.))
      IF(XMWB-19.) 26,26,23
   23 IF(XMWB-28.) 24,24,25
C*    (T.GE.15.5DEG C) AND (XM.GT.19WB) AND (XM.LE.28WB)
   24 AMT = AMT + (XMWB-19.)/100.*EXP(.61*((1.8*TJ - 28.)/60.))
      GO TO 26
C*    (T.GE.15.5DEG C) AND (XM.GT.28WB)
   25 AMT = AMT + .09*EXP(.61*((1.8*TJ - 28.)/60.))
   26 CONTINUE
C*    COMPUTE MOISTURE CONTENT MULTIPLIER FOR EQUIVALENT TIME
C*    RESTRICT MOISTURE CONTENT VALUES TO 13 - 35 WB
      IF(XMWB.LT.13.) XMDB=13./.87
      IF(XMWB.GT.35.) XMDB=35./.65
      AMM=.103*(EXP(455./XMDB**1.53)-.0084*XMDB+1.558)
C*    COMPUTE EQUIVALENT TIME INCREMENT AND SUM
      TEQ(J) = TEQ(J) + DELT/(AMT*AMM)
C*    COMPUTE PERCENT DRY MATTER LOSS
      DM(J)=.0883*(EXP(.006*TEQ(J))-1.)+.00102*TEQ(J)
C*    SUM GRAIN TEMPERATURE
      TAVE = TAVE + T(J,2)
C*    CALCURATE AVERAGE ABSOLUTE HUMIDITY
      HAVE=HAVE+H(J,2)
  103 CONTINUE
      HAVE=HAVE/IND1
C*    AVERAGE MOISTURE CONTENT
      XMAVE =XMAVE/IND1
      WBAVE=WBAVE/IND1
      DO 235 J=1,IND1
      DM(J)=DM(IND1)
```

APPENDIX D - Continued

```
C*    SUM DRY MATTER LOSSES
       DMAVE = DMAVE + DM(J)
 235   CONTINUE
C*    AVERAGE DRY MATTER LOSS
       DMAVE =DMAVE/IND1
C*    AVERAGE GRAIN TEMPERATURE
       TAVE = TAVE/IND1
       THINC=TAVE
       ITERCT=ITERCT+1
C*    CHECK IF TIME TO END, MOISTURE CONTENT LOW ENOUGH, OR TIME TO
C*    PRINT...IF NONE OF THESE GO TO BEGINNING OF TIME LOOP
       IF(WBAVE.LE..155)GOTO 12
       SHOO=TIME-PRTT
       IF(SHOO.NE.0)GO TO 451
       WATER=(XMO-XMAVE)*RHOP*DEPTH
       NODES=IND1*ITERCT
       PKCON=KCON*100./NODES
       PKAB=KAB*100./NODES
 451   IF(SHOO.GE.0.)PRTT=PRTT+2.
       IF(TIME + DELT - TT) 400,400,12
 400   IF(NEQ - 4) 11,13,13
  11   IF(TIME - PRT) 4,13,13
C*    SET FLAG IF EXIT CONDITION MET
  12   IEXIT=1
C*    MAKE FINAL CALCULATIONS AND PRINT
  13   PRT=PRT+TBTPR
       WATER=(XMO-XMAVE)*RHOP*DEPTH
C*    COMPUTE PERCENTAGE CONDENSATION AND ABSORPTION
       NODES = IND1*ITERCT
       PKCON=KCON*100./NODES
       PKAB=KAB*100./NODES
       ITERCT=0 $ KAB=0 $ KCON=0
C*    COMPUTE EQUILIBRIUM MOISTURE CONTENT FOR PRINTING
       DO 104 J=1,IND1,INDPR
       JX = J
 104   XMEPR(J)=EMC(RH(J),T(J,2))
       PRINT 212,TIME,PKCON,PKAB,XMAVE,WBAVE,WATER,DMAVE,THINC,TAVE
       PRINT 215,(XM(I),I=1,IND1,INDPR)
       PRINT 208,(WB(I),I=1,IND1,INDPR)
       PRINT 213,(T(I,2)   ,I=1,IND1,INDPR)
       PRINT 214,(DM(I),I=1,IND1,INDPR)
       PRINT 217,(H(I,2)   ,I=1,IND1,INDPR)
       PRINT 216,(RH(I),I=1,IND1,INDPR)
       PRINT 219,(XMEPR(I),I=1,IND1,INDPR)
       WRITE(1,220)  TIME,XMAVE,DMAVE
       PRINT*,NEQ1
C*    CHECK IF EXIT CONDITION HAS BEEN MET...IF NOT RETURN TO BEGIN
C*    NING OF TIME LOOP
       IF(NEQ.EQ.4) NEQ1 = NEQ1 + 1
       IF(NEQ1.EQ.4) GO TO 15
       IF(NEQ.EQ.4) GO TO 88
  15   IF(IEXIT-1) 4,14,4
  88   T(1,1) = V1 $ XM(1) = V2 $ H(1,1) = V3 $ RH(1) = V4
       GO TO 8
  14   CONTINUE
```

APPENDIX D - Continued

```
C*    ENERGY REQUIREMENT FOR FORCING AIR FROM SHEDD
      TAMBT=40. $CROSAR=23.64
      TOTP=DEPTHF*.00065*CFM**2/ALOG(1.+.156*CFM)
      HP=CFM*254.5*TOTP/5200.
      HPHOUR=HP*TIME
      BTUAIR=HPHOUR/3.929E-4
      BTUAIR=2.*BTUAIR
      TINF=TIN*9./5.+32.
      IF((TINF-TAMBT).LT.4.)TINF=TAMBT
      BTUHT=(TINF-TAMBT)*GA*.5291*TIME*CROSAR
      BTUSTIR=TSTIR*1877.15
      IF(TSTIR.GT.0.)BTUAIR=.9*BTUAIR
      TTBTU=BTUAIR+BTUHT+BTUSTIR
      ENEFF=TTBTU/(WATER*CROSAR*2.2046)
      PRINT 800
      PRINT 820
      PRINT 830,BTUAIR,BTUHT,BTUSTIR,TTBTU
      PRINT 850,ENEFF
C*                          F O R M A T S
 150  FORMAT(4F10.0,2I10/3F10.0,I10)
 200   FORMAT(2F10.2,F10.5)
 210  FORMAT(1H1,42X49HM I C H I G A N   S T A T E   U N I V E R S I T Y
     1/33X69HA G R I C U L T U R A L   E N G I N E E R I N G   D E P A R
     2 T M E N T/47X41HF I X E D   B E D   D R Y E R   M O D E L///
     3    33XA10,A10,A10,23H THINLAYER EQUATION FORA10,///
     452X31HINPUT PROPERTIES AND CONDITIONS5(/),41X,58HPROD TEMP(DEG C)
     5    DB(DECIMAL)      AIR FLOW (CMM/ M**2)
     6/39X,3(5X,F9.4,5X)/82X,F9.4,8H (KG/HR)
     74(/)11X24HHEAT CAPACITIES(JOU/KG);14X3HAIR14X7HPRODUCT10X11HWATER
     8VAPOR8X12HWATER LIQUID/34X4(12XF7.2)5(/)24X13HH T COEF CONV7X11HAT
     AMOS PRESS6X13HLAT HEAT EVAP4X18HBULK DENS DRY PROD5X14HSPEC SURF A
     BREA/14X5(10XF10.2)10(/)60X16HPROGRAM CONTROLS5(/)
     C29X19HSIMULATE A DEPTH OFF6.2,20H M  BY INCREMENTS OFF7.4,18H M  P
     DRINTING EVERYF5.2,3H  M/29X19HFOR A TOTAL TIME OFF6.2,18H HR PRINT
     EING EVERYF5.2,3H HR/29X,8HENJAIR =F12.2,12H  FROM SHEDD)
 211  FORMAT(10H1DEPTH     15F8.2)
 212  FORMAT(/   ,6X6HTIME =F6.2,20X22HPERCENT CONDENSATION =F6.2,15X20HP
     1ERCENT ABSORPTION =F6.2/6X15HAVERAGE MC DB =F6.4,11X15HAVERAGE MC
     2WB =F6.4,22X13HH2O REMOVED =F7.2/6X17HPERCENT DM LOSS =F6.3,9X23HO
     3BSEVD AVG GRAIN TEMP =,F6.2,7H  DEG C,7X20HAVERAGE GRAIN TEMP =,F6
     4.2)
 213  FORMAT(10HOTEMP      15F8.3)
 214  FORMAT(10HODM LOSS   F7.3,14F8.3)
 215  FORMAT(10HOMC DB     F7.3,14F8.3)
 208  FORMAT(10HOMC WB      F7.3,14F8.3)
 216  FORMAT(10HOREL HUM   15F8.5)
 217  FORMAT(10HOABS HUM   15F8.5)
 218  FORMAT(/29X,7HDELT = ,F7.3,4H HRS)
 219  FORMAT(10HOEQUIL MC  ,F7.3,14F8.3)
 220  FORMAT(4X,F6.2,2(4X,F6.4))
 800   FORMAT(*-*,7X,*ENERGY CONSUMPTION (BTU)*)
 820   FORMAT(*0*,2X,*FAN *,4X,*HEATING *,2X,*STIRATOR *,3X,* TOTAL *)
 830   FORMAT(* *,F9.0,3X,F9.0,3X,F7.0,3X,F9.0)
 850   FORMAT(*0*,*ENERGY EFFICIENCY = *,F5.0,* BTU/LBH2O*)
      END
      BLOCKDATA
      COMMON /PRPRTY/SA,CA,CP,CV,CW,RHOP,HFG
      COMMON/PRESS/PATM
      DATA SA,CA,CP,CV,CW,RHOP,HFG/784.12,1012.46,1121.24,1882.68,
     +4183.74,620.07,2.326E+06/
      DATA PATM/98595.0251/
      END
```

APPENDIX D - Continued

```
      FUNCTION EMC(RH,T)
C*
C*                   S.F.DEBOER, PROGRAMMER IN ENGLISH UNITS
C*                                AND
C*                   EDISON W. RUGUMAYO, CONVERTER TO SI UNITS
C*    DESCRIPTION
C*             FUNCTION  COMPUTES EQUILIBRIUM MOISTURE CONTENT OF CORN
C*    FROM A RELATIVE HUMIDITY AND TEMPERATURE
C*    CHECK TEMPERATURE TO DETERMINE EQUATION TO BE USED
      IF(T - 112.778) 234,235,235
C*                   DEBOER EQUATIONS
C*    CHECK IF RH IS GREATER THAN .50 ..IF SO GO TO SECOND PART
  234 IF(RH - .50) 300,300,309
C*    PART ONE  RH .LE. .50 ONLY
  300 F1 = -.00070596*T + .0874496
      F2 = -.00078354*T + .1188704
      F3 =-.00096462*T + .1474512
      S1 = 13.838*(-9.*F1 + 6.*F2 - F3)
      S2 = 13.838*(4.*F3 - 9.*F2 + 6.*F1)
      B = RH - .17
C*    FIND INTERVAL IN WHICH RH LIES AND COMPUTE EQUILIBRIUM MOISTURE
      IF (B) 301,301,302
  301 EMC = (S1*RH*RH*RH/1.02 + (F1/.17 - S1*.02833)*RH)
      RETURN
  302 IF(RH - .34) 303,303,304
  303 A = .34 - RH
      EMC = (S1*A*A*A/1.02 + S2*B*B*B/1.02 + (F2/.17 - S2*.02833)*B +
     +(F1/.17 - S1*.02833)*A)
      RETURN
  304 A = .51 - RH
      EMC = S2*A*A*A/1.02 + (F3/.17)*(RH - .34) + (F2/.17 - S2*.02833)
     +*A
      RETURN
C*    PART TWO---RH.GT. .50 ONLY
C*    COMPUTE CONSTANTS
  309 F0 = -.00096714*T + .1452064
      F1 = -.00127350*T + .1848600
      F2 = -.00134082*T + .2293632
      F3 = -.00192780*T + .3588280
      S1 = 13.838*(4.*F0 - 9.*F1 + 6.*F2 - F3)
      S2 = 13.838*(4.*F3 - 9.*F2 + 6.*F1 - F0)
      B = RH - .66
      IF(B) 305,305,306
C*    FIND INTERVAL IN WHICH RH LIES AND COMPUTE EQUILIBRIUM MOISTURE
  305 A = RH - .49
      EMC = S1*A*A*A/1.02 + (F1/.17 - S1*.02833)*A + (F0/.17)*(.66 - RH)
      RETURN
  306 IF(RH - .83) 307,307,308
  307 A = .83 - RH
      EMC = S1*A*A*A/1.02 + S2*B*B*B/1.02 + (F2/.17 - S2*.02833)*B +
     +(F1/.17 - S1*.028333)*A
      RETURN
  308 A = 1.0 - RH
      EMC = S2*A*A*A/1.02 + (F3/.17)*(RH - .83) + (F2/.17 - S2*.028333)
     1*A
      RETURN
C*                            THOMPSON   EQUATION
C*    T.GE. 113 DEGREES CELCUS
  235 EMC = .01*SQRT((-ALOG(1. - RH))/(.0000382*(1.8*T + 82.)))
      RETURN
      END
```

APPENDIX D - Continued

```
*DECK LAYEQ
      SUBROUTINE LAYEQ
C*
C*                          L.E. LEREW, PROGRAMMER
C*
C*                          E.W.RUGUMAYO, SI-UNIT CONVERTER AND
C*                          MODIFIER  1978
C*
C*    DESCRIPTION
C*         SUBROUTINE TO FIND THE MOISTURE CONTENT BASED ON EQUATIONS
C*    BY M.A.SABBAH, E.W.RUGUMAYO ,MISRA AND P.M.DEL GUIDICE
C*
C*    USAGE
C*         USED IN THE FIXED BED AND CROSS FLOW MODELS WITH GRAIN
C*    TEMPERATURE LESS THAN 26.7 DEG CELCIUS ( 80.0 F )
C*
      COMMON/MAIN/XMC,TH,RH,DELT,CMM,XMO,KAB,TIME
      COMMON/NAME/INAME,IPROD,NEQ,NEQ1
      DIMENSION INAME(3)
      DATA INAME,IPROD/10HSABBAH AND,10H RUGUMAYO ,10HAND MISRA ,10H COR
     1N    /
      DATA TGUESS/1.0/
C*    CALL READYTH FOR PRELIMINARY CHECKS AND CALCULATIONS
      CALL READYTH(TXMO,DELM,XME,IOOPS,XMR)
      IF(IOOPS - 1) 1,20,1
    1 RSQ = RH*RH
      X = SQRT(6.0142 + .1453E-3*RSQ) - (1.8*TH + 32.)*SQRT(.3353E-3 +
     1.3E-7*RSQ)
      Y = .1245 - .2197E-2*RH - (1.8*TH + 32.)*(.23E-4*RH + .58E-4)
      R=25.592-38.6298*XMC+26.6824*ALOG10(XMC)-0.0044*(XMC*2.)*
     2(TH+273.16)*EXP(RSQ)
      K = 0
      T1 = TGUESS
C*    CHECK IF DERIVATIVE IS VERY LARGE.. IF SO ASSIGN T1 = 0.0
      IF(XMR.LT..999) GO TO 2
      T1=0.0
      GO TO 4
C*    CHECK FOR EQUILIBRIUM CONDITIONS
    2 IF(XMC - XME.LT..0001) GO TO 70
      U=ALOG(-ALOG(XMR))
      IF(NEQ1.EQ.1) U=ALOG(XMR)
C*    IF Y IS POSITIVE, EQUATION WILL NEVER REACH XME
C*    T1MAX IS THE CLOSEST APPROACH USED TO LIMIT SEARCH .
      T1MAX = 2000.
      IF(Y.LE.0.) GO TO 3
      IF(X.LE.0.) GO TO 3
      IF(R.GE.0.) GO TO 3
      T1MAX = (0.664/(X*Y))**(1.0/Y)
C*    NEWTON - RAPHSON TECHNIQUE TO FIND EQUIVALENT TIME
    3 Z1 = X*T1**Y - .664*ALOG(T1) + U
      IF(NEQ1.EQ.1) Z1=U-R*T1
      IF(ABS(Z1).LT..001) GO TO 4
      Z2 = X*Y*T1**(Y-1.) - .664/T1
      IF(NEQ1.EQ.1) Z2=-R
      T2 = T1 - Z1/Z2
      K = K + 1
```

APPENDIX D - Continued

```
      IF(T2.LE.0.0) T2 = T1/5.
      IF(T2.GE.T1MAX) GO TO 4
      T1 = T2
      IF(K.LT.20)  GO TO 3
      PRINT 210,K
  210 FORMAT(33HOTHE METHOD HAS NOT CONVERGED IN I2,11H ITERATIONS)
      PRINT 211,XMC,TH,RH,XME
  211 FORMAT(* LAYEQ.  XMC=*F8.5* TH=*F8.3* RH=*F8.5* XME=*F8.5)
C*    ADD DELT TO EQUIVALENT TIME,SOLVE FOR NEW M AND RETURN
    4 T1=T1+DELT
C*    CORN THIN LAYER EQUATIONS FOR LOW TEMPERATURE DRYING
C*
    5 IF(TIME.LE.0.0) DELT = 0.0
C*    RUGUMAYO DRYING EQUATION ONE FOR WHOLE TEMPERATURE RANGE
      IF(NEQ1.EQ.1) XMC=DELM*EXP(R*T1)+XME
      IF(NEQ1.EQ.1) RETURN
      IF(NEQ1.EQ.2) GO TO 6
C*    SABBAH DRYING EQUATION
      IF(NEQ1.EQ.3) XMC = DELM*EXP(-EXP(-X*T1**Y)*T1**.664) + XME
      IF(NEQ1.EQ.3) RETURN
      IF(NEQ1.EQ.4) GO TO 21
C*    MISRA(1978) DRYING EQUATION
    6 XMC = DELM*EXP(-(EXP(-7.1735 + 1.2793*ALOG(1.8*TH + 32.0) +
     20.0061*CMM))*TIME**(0.0811*ALOG(100.0*RH) + 0.0078*XMO)) + XME
      IF(NEQ1.EQ.2) RETURN
   21 NEQ1 = 1
      GO TO 5
C*
C*    ABSORPTION SIMULATION
C*    FIND NEW M AND INCREMENT COUNTER
   20 DIV = -4.309*PSDB(TH + 273.16)**(.466*RH)*RH*RH*RH
      IF(NEQ1.NE.1) GO TO 22
      RSQ=RH*RH
      R1=162.1179-487.9552*XMC+118.6144
     1*ALOG10(XMC)+0.69658*(TH+273.16)*(XMC*2.)*EXP(RSQ)
C
   22 IF(TIME.LE.0.0) DELT = 0.0
C*    RUGUMAYO ABSORPTION EQUATION FOR WHOLE LOW TEMPERATURE RANGE
      IF(NEQ1.EQ.1) XMC = DELM*EXP(R1*T1)+XME
      IF(NEQ1.EQ.1) GO TO 60
      IF(NEQ1.EQ.2) GO TO 25
C*    DEL GUIDICE EQUATION (1959)
      IF(NEQ1.EQ.3) XMC = (XMC - XME)*EXP(DIV*DELT) + XME
      IF(NEQ1.EQ.3) GO TO 60
C*    MISRA(1978) REWETTING EQUATION
   25 XMC = DELM*EXP(-(EXP(-8.5122 + 1.2178*ALOG(1.8*TH + 32.0) +
     20.0864*XMO))*TIME**( 2.1876 - 1.67*RH)) + XME
      IF(NEQ1.EQ.2) GO TO 60
      NEQ1 = 1
      GO TO 22
   60 IF(NEQ.NE.4) KAB = KAB + 1
      IF(NEQ.EQ.4.AND.NEQ1.EQ.3) KAB = KAB + 1
      RETURN
   70 XMC = XME
      RETURN
      END
```

APPENDIX D - Continued

```
      SUBROUTINE READYTH(TXMO,DELM,XME,IOOPS,XMR)
C*
C*
C*   DESCRIPTION
C*   SUBROUTINE MAKES PRELIMINARY CHECKS AND CALCULATIONS
C*   FOR THIN LAYER EQUATIONS
C*
C*   USAGE
C*   USED WITH LAYEQ IN FIXED AND CROSS FLOW DRYER MODELS
C*
      COMMON/MAIN/XMC,TH,RH,DELT,CMM,XMO,KAB,TIME
      COMMON/NAME/INAME,IPROD,NEQ,NEQ1
      DIMENSION INAME(3)
      IOOPS = 0
C* COMPUTE EQUILIBRIUM MOISTURE CONTENT, COMPARE TO PRESENT
C*    MOISTURE CONTENT... IF GREATER SET IOOPS = 1
      XME = EMC(RH,TH)
      IF(XME - XMC) 2,1,1
    1 IOOPS = 1
C*   COMPARE PRESENT MOISTURE CONTENT TO INITIAL MOISTURE CONTENT
C*   SET TXMO = THE LARGER VALUE
    2 IF(XMO - XMC) 3,4,4
    3 TXMO = XMC
      GO TO 5
    4 TXMO = XMO
C*   COMPUTE MOISTURE RATIO
    5 DELM = TXMO - XME
      XMR = (XMC - XME)/DELM
      RETURN
      END
      FUNCTION SOLVE(HJ2)
C*
C*   COMPUTES T(J,2), XMT, RH(J) AND ICON GIVEN H(J,2)
C*   SOLVE RETURNS THE DIFFERENCE BETWEEN THE COMPUTED M AND
C*   THE M PREDICTED BY THE DRYING EQUATION
C*
      COMMON /ARRAYS/ T(51,2),H(51,2),XM(51),RH(51)
      COMMON /CONS/ CON1,CON2,CON3,CON4,CON5,CON6,CON7,CON12,CON13
      COMMON /FLAGS/ J,JM,ICON
      COMMON /MAIN/ XMT,THT,RHT,DELT,CMM,XMO,KAB,TIME
      COMMON /PRPRTY/ SA,CA,CP,CV,CW,RHOP,HFG
      F(T) = T + 273.16
      DATA RHC /.9999999999/
      ICON=0
      H(J,2)=HJ2
C*   T EQUATION
      T1=CON1*(H(J,2)-H(JM,2))
      T2=CON1*(CA+CV*H(JM,2))
      T3=CON4*(CP+CW*XM(J))
      T(J,2)=(-T1*CON3+T2*T(JM,2)+T3*T(J,1))/(-T1*CON2+T2+T3)
      IF(T(J,2).LT.-17.8) GO TO 7
      TABS=F(T(J,2))
C*   COMPUTE RH AND CHECK FOR CONDENSATION
      RH(J)=RHDBHA(TABS,H(J,2))
      IF(RH(J)-RHC)111,7,7
```

APPENDIX D - Continued

```
C*    CONDENSATION SIMULATOR
    7 TS=(T2*T(JM,2)+T3*T(J,1))/(T2+T3) $ TABS=F(TS)
      HS=HADBRH(TABS,RHC)
      DHDT=HS-HADBRH(TABS-1.00,RHC)
      T1=HS-H(JM,2)-DHDT*TS
      A=CON12*DHDT
      B=CON12*T1-T2-T3-CON13*DHDT
      C=T2*T(JM,2)+T3*T(J,1)-CON13*T1
      T(J,2)=(-B-SQRT(B*B-4.*A*C))/(2.*A)
      H(J,2)=HS+DHDT*(T(J,2)-TS)
      RH(J)=RHDBHA(F(T(J,2)),H(J,2))
      ICON=1
C*   FIND M ACCORDING TO THIN LAYEE DRYING EQUATION
  111 XMT=XM(J) $ THT=T(J,2) $ RHT=RH(J)
      CALL LAYEQ
      SOLVE=XMT-XM(J)+CON6*(HJ2-H(JM,2))
C*   M EQUATION
      XMT=XM(J)-CON6*(H(J,2)-H(JM,2))
      RETURN
      END
*EOR
 .2996      10.        6.51    3.6577560        1         3
  700.        4.        1.            3
*EOF
```

APPENDIX D - Continued

```
                    M I C H I G A N   S T A T E   U N I V E R S I T Y
          A G R I C U L T U R A L   E N G I N E E R I N G   D E P A R T M E N T
                         F I X E D   B E D   D R Y E R   M O D E L

          SABBAH AND RUGUMAYO AND MISRA  THINLAYER EQUATION FOR CORN

                         INPUT PROPERTIFS AND CONDITIONS

               PROD TEMP(DEG C)     DB(DECIMAL)     AIR FLOW (CMM/ M**2)
                  60.0000               .2996                6.5900
                                                           333.7087 (KG/HR)

HEAT CAPACITIES(JOU/KG):    AIR              PRODUCT        WATER VAPOR       WATER LIQUID
                          1012.46            1121.24         1882.68           4183.74

      H T COEF CONV     ATMOS PRESS     LAT HFAT EVAP    BULK DENS DRY PROD    SPEC SURF AREA
       111703.91         98595.03       2326000.00             620.07              784.12

                                 PROGRAM CONTROLS

          SIMULATE A DEPTH OF  3.66 M  BY INCREMENTS OF  .3333 M  PRINTING EVERY  .33  M
          FOR A TOTAL TIME OF800.00 HR PRINTING EVERY 4.00 HR
          ENJAIR = 31237256.77  FROM SHEDD

          DELT =   1.000 HRS
```

APPENDIX D - Continued

DEPTH	0.00	.33	.67	1.00	1.33	1.67	2.00	2.33	2.67	3.00	3.33

TIME = 1.00 PERCENT CONDENSATION = 0.00 PERCENT ABSORPTION = 0.00
AVERAGE MC DB = .2803 AVERAGE MC WB = .2187 H2O REMOVED = 43.79
PERCENT DM LOSS = .011 OBSEVD AVG GRAIN TEMP = 40.75 DEG C AVERAGE GRAIN TEMP = 40.75

MC DB	.220	.280	.281	.283	.285	.286	.287	.289	.290	.290	.291
MC WB	.181	.219	.220	.221	.222	.222	.223	.224	.225	.225	.226
TEMP	14.520	29.211	35.964	39.767	42.363	44.363	46.001	47.382	48.568	49.599	50.503
DM LOSS	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011	.011
ABS HUM	.00555	.01751	.02876	.03902	.04827	.05660	.06413	.07096	.07718	.08286	.08806
REL HUM	.52758	.66607	.73520	.79929	.85001	.88720	.91402	.93355	.94801	.95892	.96728
EQUIL MC	.140	.149	.152	.164	.182	.199	.213	.223	.230	.236	.240

TIME = 4.00 PERCENT CONDENSATION = 0.00 PERCENT ABSORPTION = 0.00
AVERAGE MC DB = .2650 AVERAGE MC WB = .2093 H2O REMOVED = 78.55
PERCENT DM LOSS = .027 OBSEVD AVG GRAIN TEMP = 20.41 DEG C AVERAGE GRAIN TEMP = 20.41

MC DB	.213	.265	.268	.268	.268	.269	.271	.272	.273	.274	.275
MC WB	.175	.209	.211	.211	.212	.212	.213	.214	.214	.215	.216
TEMP	14.520	12.033	13.486	15.691	18.025	20.310	22.431	24.420	26.204	27.886	29.477
DM LOSS	.027	.027	.027	.027	.027	.027	.027	.027	.027	.027	.027
ABS HUM	.00555	.00734	.00847	.00989	.01161	.01353	.01572	.01798	.02039	.02281	.02529
REL HUM	.52758	.81812	.85704	.86618	.87463	.88103	.89578	.90573	.92015	.92936	.93590
EQUIL MC	.140	.208	.226	.228	.230	.231	.237	.241	.248	.252	.254

TIME = 8.00 PERCENT CONDENSATION = 0.00 PERCENT ABSORPTION = 0.00
AVERAGE MC DB = .2592 AVERAGE MC WB = .2057 H2O REMOVED = 91.70
PERCENT DM LOSS = .033 OBSEVD AVG GRAIN TEMP = 13.01 DEG C AVERAGE GRAIN TEMP = 13.01

MC DB	.205	.256	.265	.265	.265	.265	.265	.266	.266	.266	.267
MC WB	.170	.204	.209	.210	.209	.209	.210	.210	.210	.210	.211
TEMP	14.520	11.399	10.640	10.803	11.273	11.837	12.582	13.545	14.467	15.467	16.526
DM LOSS	.033	.033	.033	.033	.033	.033	.033	.033	.033	.033	.033
ABS HUM	.00555	.00676	.00715	.00730	.00745	.00780	.00822	.00863	.00921	.00990	.01067
REL HUM	.52758	.78686	.87475	.86325	.87351	.88060	.88242	.86962	.87351	.87952	.88501
EQUIL MC	.140	.197	.241	.246	.239	.243	.243	.233	.234	.237	.239

TIME = 12.00 PERCENT CONDENSATION = 0.00 PERCENT ABSORPTION = 0.00
AVERAGE MC DB = .2568 AVERAGE MC WB = .2042 H2O REMOVED = 97.01
PERCENT DM LOSS = .034 OBSEVD AVG GRAIN TEMP = 11.29 DEG C AVERAGE GRAIN TEMP = 11.29

MC DB	.199	.249	.262	.265	.265	.264	.264	.264	.264	.264	.264
MC WB	.166	.199	.208	.209	.209	.209	.209	.209	.209	.209	.209
TEMP	14.520	11.709	10.689	10.407	10.431	10.517	10.632	10.851	11.099	11.460	11.825
DM LOSS	.034	.034	.034	.034	.034	.034	.034	.034	.034	.034	.034
ABS HUM	.00555	.00663	.00697	.00712	.00717	.00722	.00727	.00732	.00747	.00762	.00787
REL HUM	.52758	.75544	.84980	.88431	.88904	.89005	.88931	.88236	.88556	.88177	.88864
EQUIL MC	.140	.188	.225	.247	.250	.251	.250	.245	.247	.244	.248

APPENDIX D - Continued

TIME = 36.00 PERCENT CONDENSATION = 0.00 PERCENT ABSORPTION = 18.18
AVERAGE MC DB = .2491 AVERAGE MC WB = .1991 H2O REMOVED = 114.58
PERCENT DM LOSS = .041 OBSEVD AVG GRAIN TEMP = 11.05 DEG C AVERAGE GRAIN TEMP = 11.05

MC DB	.180	.216	.243	.257	.263	.262	.263	.264	.263	.264	.264
MC WB	.153	.178	.195	.204	.208	.208	.208	.209	.208	.209	.209
TEMP	14.520	12.982	11.483	10.633	10.482	10.334	10.193	10.235	10.187	10.263	10.183
DM LOSS	.041	.041	.041	.041	.041	.041	.041	.041	.041	.041	.041
ABS HUM	.00555	.00615	.00672	.00705	.00710	.00715	.00720	.00715	.00720	.00715	.00720
REL HUM	.52758	.64516	.77745	.86223	.87710	.89194	.90659	.89788	.90698	.89616	.90720
EQUIL MC	.140	.166	.194	.233	.242	.253	.263	.257	.264	.256	.264

TIME = 40.00 PERCENT CONDENSATION = 0.00 PERCENT ABSORPTION = 18.18
AVERAGE MC DB = .2480 AVERAGE MC WB = .1983 H2O REMOVED = 117.12
PERCENT DM LOSS = .042 OBSEVD AVG GRAIN TEMP = 11.09 DEG C AVERAGE GRAIN TEMP = 11.09

MC DB	.178	.213	.239	.255	.262	.262	.263	.264	.264	.264	.264
MC WB	.151	.175	.193	.203	.208	.208	.208	.209	.209	.209	.209
TEMP	14.520	13.095	11.507	10.691	10.554	10.410	10.262	10.183	10.316	10.181	10.320
DM LOSS	.042	.042	.042	.042	.042	.042	.042	.042	.042	.042	.042
ABS HUM	.00555	.00610	.00672	.00705	.00710	.00715	.00720	.00725	.00719	.00724	.00717
REL HUM	.52758	.63603	.77653	.85892	.87284	.88743	.90242	.91341	.89893	.91333	.89570
EQUIL MC	.140	.164	.194	.231	.239	.249	.260	.268	.258	.268	.255

TIME = 44.00 PERCENT CONDENSATION = 0.00 PERCENT ABSORPTION = 18.18
AVERAGE MC DB = .2468 AVERAGE MC WB = .1975 H2O REMOVED = 119.72
PERCENT DM LOSS = .043 OBSEVD AVG GRAIN TEMP = 11.12 DEG C AVERAGE GRAIN TEMP = 11.12

MC DB	.176	.209	.235	.253	.261	.262	.263	.264	.264	.264	.264
MC WB	.150	.173	.190	.202	.207	.207	.208	.209	.209	.209	.209
TEMP	14.520	13.196	11.722	10.793	10.425	10.319	10.275	10.331	10.263	10.284	10.219
DM LOSS	.043	.043	.043	.043	.043	.043	.043	.043	.043	.043	.043
ABS HUM	.00555	.00607	.00663	.00700	.00715	.00720	.00725	.00716	.00721	.00716	.00721
REL HUM	.52758	.62789	.75554	.84758	.88696	.89947	.90830	.89407	.90433	.89693	.90701
EQUIL MC	.140	.162	.188	.224	.249	.258	.265	.254	.262	.256	.264

STIRRING OCCURRED AT 48.00 HRS

TIME = 48.00 PERCENT CONDENSATION = 0.00 PERCENT ABSORPTION = 13.64
AVERAGE MC DB = .2457 AVERAGE MC WB = .1972 H2O REMOVED = 122.35
PERCENT DM LOSS = .045 OBSEVD AVG GRAIN TEMP = 11.38 DEG C AVERAGE GRAIN TEMP = 11.38

MC DB	.245	.244	.245	.246	.246	.246	.246	.246	.246	.246	.246
MC WB	.197	.196	.197	.197	.197	.197	.197	.197	.197	.197	.197
TEMP	14.520	11.611	11.006	10.925	10.890	10.984	11.025	11.043	11.050	11.054	11.055
DM LOSS	.045	.045	.045	.045	.045	.045	.045	.045	.045	.045	.045
ABS HUM	.00555	.00647	.00679	.00694	.00709	.00714	.00719	.00724	.00729	.00734	.00739
REL HUM	.52758	.74274	.81052	.83269	.85248	.85309	.85667	.86155	.86699	.87267	.87846
EQUIL MC	.140	.185	.206	.216	.227	.227	.229	.232	.235	.239	.242

APPENDIX D - Continued

TIME = 92.00
AVERAGE MC DB = .2294
PERCENT DM LOSS = .054

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1863
OBSEVD AVG GRAIN TEMP = 11.52 DEG C

PERCENT ABSORPTION = 9.09
H2O REMOVED = 159.31
AVERAGE GRAIN TEMP = 11.52

MC DB	.178	.199	.215	.231	.237	.241	.242	.243	.245	.246	.245
MC WB	.151	.166	.177	.187	.192	.194	.195	.196	.197	.197	.197
TEMP	14.520	13.489	12.443	11.653	11.230	10.830	10.684	10.545	10.421	10.408	10.504
DM LOSS	.054	.054	.054	.054	.054	.054	.054	.054	.054	.054	.054
ABS HUM	.00555	.00595	.00635	.00666	.00682	.00697	.00702	.00707	.00712	.00717	.00710
REL HUM	.52758	.60455	.69067	.76183	.80188	.84140	.85562	.86966	.88304	.88992	.87667
EQUIL MC	.140	.157	.174	.189	.202	.221	.229	.237	.246	.251	.242

STIRRING OCCURRED AT 96.00 HRS

TIME = 96.00
AVERAGE MC DB = .2283
PERCENT DM LOSS = .055

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1858
OBSEVD AVG GRAIN TEMP = 11.75 DEG C

PERCENT ABSORPTION = 6.82
H2O REMOVED = 161.78
AVERAGE GRAIN TEMP = 11.75

MC DB	.228	.227	.228	.228	.228	.228	.228	.228	.228	.228	.228
MC WB	.186	.185	.186	.186	.186	.186	.186	.186	.186	.186	.186
TEMP	14.528	12.094	11.503	11.372	11.313	11.287	11.387	11.431	11.451	11.459	11.463
DM LOSS	.055	.055	.055	.055	.055	.055	.055	.055	.055	.055	.055
ABS HUM	.00555	.00625	.00652	.00667	.00682	.00697	.00702	.00707	.00712	.00717	.00722
REL HUM	.52758	.69528	.75345	.77737	.79775	.81650	.81689	.82024	.82498	.83015	.83566
EQUIL MC	.140	.175	.188	.194	.201	.208	.208	.210	.212	.214	.217

TIME =100.00
AVERAGE MC DB = .2262
PERCENT DM LOSS = .055

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1845
OBSEVD AVG GRAIN TEMP = 11.58 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 166.43
AVERAGE GRAIN TEMP = 11.58

MC DB	.216	.223	.226	.227	.228	.228	.228	.228	.228	.228	.228
MC WB	.177	.182	.185	.185	.185	.186	.186	.186	.186	.186	.186
TEMP	14.520	12.629	11.818	11.382	11.151	11.029	10.972	10.956	10.965	10.984	11.005
DM LOSS	.055	.055	.055	.055	.055	.055	.055	.055	.055	.055	.055
ABS HUM	.00655	.00627	.00657	.00672	.00677	.00682	.00687	.00692	.00697	.00702	.00707
REL HUM	.52758	.67382	.74334	.78238	.80027	.81265	.82167	.82845	.83389	.83874	.84348
EQUIL MC	.140	.171	.185	.196	.202	.207	.211	.214	.217	.219	.221

TIME =104.00
AVERAGE MC DB = .2246
PERCENT DM LOSS = .056

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1834
OBSEVD AVG GRAIN TEMP = 11.56 DEG C

PERCENT ABSORPTION = 9.09
H2O REMOVED = 170.17
AVERAGE GRAIN TEMP = 11.56

MC DB	.207	.219	.224	.226	.227	.228	.228	.228	.228	.228	.228
MC WB	.172	.179	.183	.185	.185	.185	.186	.186	.186	.186	.186
TEMP	14.520	12.911	11.651	11.440	11.109	11.020	10.919	10.820	10.800	10.847	10.874
DM LOSS	.056	.056	.056	.056	.056	.056	.056	.056	.056	.056	.056
ABS HUM	.00555	.00617	.00657	.00672	.00687	.00692	.00697	.00702	.00707	.00702	.00697
REL HUM	.52758	.65065	.74269	.76034	.81529	.82599	.83749	.84896	.85609	.84721	.83975

APPENDIX D - Continued

STIRRING OCCURRED AT 144.00 HRS

TIME =144.00
AVERAGE MC DB = .2132
PERCENT DM LOSS = .062

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1757
OBSEVD AVG GRAIN TEMP = 12.12 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 196.07
AVERAGE GRAIN TEMP = 12.12

MC DB	.213	.213	.213	.213	.213	.213	.213	.213	.213	.213	.213
MC WB	.176	.175	.176	.176	.176	.176	.176	.176	.176	.176	.176
TEMP	14.520	12.573	11.913	11.759	11.689	11.771	11.807	11.824	11.832	11.835	11.836
DM LOSS	.062	.062	.062	.062	.062	.062	.062	.062	.062	.062	.062
ABS HUM	.00555	.00602	.00629	.00644	.00659	.00664	.00669	.00674	.00679	.00684	.00689
REL HUM	.52758	.64886	.70847	.73261	.75293	.75450	.75827	.76304	.76825	.77367	.77918
EQUIL MC	.140	.167	.178	.183	.187	.187	.188	.190	.191	.192	.194

TIME =148.00
AVERAGE MC DB = .2116
PERCENT DM LOSS = .062

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1747
OBSEVD AVG GRAIN TEMP = 11.99 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 199.49
AVERAGE GRAIN TEMP = 11.99

MC DB	.205	.209	.211	.212	.212	.213	.213	.213	.213	.213	.213
MC WB	.170	.173	.174	.175	.175	.176	.176	.176	.176	.176	.176
TEMP	14.520	13.173	12.336	11.876	11.567	11.482	11.422	11.393	11.384	11.388	11.396
DM LOSS	.062	.062	.062	.062	.062	.062	.062	.062	.062	.062	.062
ABS HUM	.00555	.00606	.00636	.00651	.00666	.00671	.00676	.00681	.00686	.00691	.00696
REL HUM	.52758	.62835	.69608	.73418	.76644	.77644	.78528	.79258	.79877	.80435	.80969
EQUIL MC	.140	.162	.175	.183	.191	.194	.196	.199	.201	.203	.205

TIME =152.00
AVERAGE MC DB = .2103
PERCENT DM LOSS = .063

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1737
OBSEVD AVG GRAIN TEMP = 11.97 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 202.54
AVERAGE GRAIN TEMP = 11.97

MC DB	.199	.206	.209	.211	.212	.213	.213	.213	.213	.213	.213
MC WB	.166	.171	.173	.174	.175	.175	.175	.175	.175	.175	.175
TEMP	14.520	13.287	12.501	12.077	11.676	11.536	11.405	11.288	11.192	11.119	11.067
DM LOSS	.063	.063	.063	.063	.063	.063	.063	.063	.063	.063	.063
ABS HUM	.00555	.00603	.00633	.00648	.00663	.00668	.00673	.00678	.00683	.00688	.00693
REL HUM	.52758	.62050	.68520	.72108	.75738	.77013	.78260	.79447	.80538	.81516	.82382
EQUIL MC	.140	.161	.173	.180	.188	.192	.196	.200	.204	.208	.212

TIME =156.00
AVERAGE MC DB = .2091
PERCENT DM LOSS = .063

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1729
OBSEVD AVG GRAIN TEMP = 12.02 DEG C

PERCENT ABSORPTION = 2.27
H2O REMOVED = 205.29
AVERAGE GRAIN TEMP = 12.02

MC DB	.195	.203	.207	.210	.211	.212	.212	.212	.212	.212	.212
MC WB	.163	.169	.172	.174	.174	.175	.175	.175	.175	.175	.175
TEMP	14.520	13.372	12.609	12.200	11.789	11.631	11.477	11.329	11.191	11.065	10.988
DM LOSS	.063	.063	.063	.063	.063	.063	.063	.063	.063	.063	.063
ABS HUM	.00555	.00600	.00629	.00644	.00659	.00664	.00669	.00674	.00679	.00684	.00689
REL HUM	.52758	.61384	.67625	.71108	.74741	.76093	.77444	.78783	.80092	.81354	.82362
EQUIL MC	.140	.159	.172	.178	.186	.189	.193	.197	.202	.207	.212

APPENDIX D - Continued

TIME =180.00
AVERAGE MC DB = .2030
PERCENT DM LOSS = .066

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1687
OBSEVD AVG GRAIN TEMP = 12.33 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 219.09
AVERAGE GRAIN TEMP = 12.33

MC DB	.178	.189	.197	.204	.205	.208	.210	.210	.210	.210	.211
MC WB	.151	.159	.164	.170	.170	.172	.174	.174	.174	.174	.174
TEMP	14.520	13.756	13.112	12.695	12.298	11.901	11.753	11.605	11.458	11.311	11.166
DM LOSS	.066	.066	.066	.066	.066	.066	.066	.066	.066	.066	.066
ABS HUM	.00555	.00585	.00610	.00626	.00641	.00656	.00661	.00666	.00671	.00676	.00681
REL HUM	.52758	.58391	.63470	.66903	.70296	.73832	.75117	.76421	.77743	.79080	.80428
EQUIL MC	.140	.153	.164	.170	.176	.184	.187	.190	.194	.198	.203

TIME =184.00
AVERAGE MC DB = .2021
PERCENT DM LOSS = .066

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1681
OBSEVD AVG GRAIN TEMP = 12.38 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 221.13
AVERAGE GRAIN TEMP = 12.38

MC DB	.176	.187	.195	.203	.204	.207	.210	.210	.210	.210	.210
MC WB	.150	.158	.163	.169	.169	.171	.174	.174	.174	.174	.174
TEMP	14.520	13.806	13.216	12.744	12.340	11.949	11.810	11.669	11.525	11.380	11.235
DM LOSS	.066	.066	.066	.066	.066	.066	.066	.066	.066	.066	.066
ABS HUM	.00555	.00583	.00608	.00624	.00639	.00654	.00659	.00664	.00669	.00674	.00679
REL HUM	.52758	.58008	.62838	.66467	.69875	.73362	.74598	.75862	.77155	.78475	.79818
EQUIL MC	.140	.152	.162	.169	.176	.183	.185	.189	.192	.196	.201

TIME =188.00
AVERAGE MC DB = .2012
PERCENT DM LOSS = .066

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1674
OBSEVD AVG GRAIN TEMP = 12.43 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 223.11
AVERAGE GRAIN TEMP = 12.43

MC DB	.175	.185	.194	.202	.203	.206	.210	.210	.210	.210	.210
MC WB	.149	.156	.163	.168	.169	.171	.173	.173	.173	.173	.174
TEMP	14.520	13.853	13.380	12.850	12.417	12.008	11.747	11.666	11.553	11.425	11.288
DM LOSS	.066	.066	.066	.066	.066	.066	.066	.066	.066	.066	.066
ABS HUM	.00555	.00581	.00598	.00614	.00629	.00644	.00659	.00664	.00669	.00674	.00679
REL HUM	.52758	.57650	.61145	.65006	.68494	.72019	.74959	.75926	.77066	.78298	.79587
EQUIL MC	.140	.151	.159	.167	.173	.180	.186	.189	.192	.196	.200

STIRRING OCCURRED AT 192.00 HRS

TIME =192.00
AVERAGE MC DB = .2004
PERCENT DM LOSS = .067

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1669
OBSEVD AVG GRAIN TEMP = 12.60 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 224.99
AVERAGE GRAIN TEMP = 12.60

MC DB	.200	.200	.200	.200	.200	.201	.201	.201	.201	.201	.201
MC WB	.167	.167	.167	.167	.167	.167	.167	.167	.167	.167	.167
TEMP	14.520	13.004	12.536	12.321	12.223	12.293	12.325	12.340	12.347	12.350	12.351
DM LOSS	.067	.067	.067	.067	.067	.067	.067	.067	.067	.067	.067
ABS HUM	.00555	.00590	.00605	.00620	.00635	.00640	.00645	.00650	.00655	.00660	.00665
REL HUM	.52758	.61817	.65347	[illegible]	.69976	.70199	.70593	.71067	.71576	.72103	.72637
EQUIL MC	.140	.161	.168	.172	.176	.176	.177	.178	.179	.180	.181

APPENDIX D - Continued

TIME =236.00 AVERAGE MC DB = .1910 PERCENT DM LOSS = .070 | PERCENT CONDENSATION = 0.00 AVERAGE MC WB = .1603 OBSEVD AVG GRAIN TEMP = 12.90 DEG C | PERCENT ABSORPTION = 0.00 H20 REMOVED = 246.30 AVERAGE GRAIN TEMP = 12.90

MC DB	.172	.180	.188	.190	.190	.195	.197	.197	.197	.197	.197
MC WB	.147	.153	.158	.159	.160	.163	.165	.165	.165	.165	.165
TEMP	14.520	14.000	13.654	13.289	12.913	12.666	12.486	12.328	12.177	12.030	11.887
DM LOSS	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070
ABS HUM	.00555	.00580	.00595	.00610	.00625	.00630	.00635	.00640	.00645	.00650	.00655
REL HUM	.52758	.57019	.59808	.62777	.65900	.67506	.68845	.70105	.71351	.72597	.73842
EQUIL MC	.140	.149	.156	.162	.168	.171	.174	.176	.178	.181	.184

STIRRING OCCURRED AT 240.00 HRS

TIME =240.00 AVERAGE MC DB = .1903 PERCENT DM LOSS = .070 | PERCENT CONDENSATION = 0.00 AVERAGE MC WB = .1599 OBSEVD AVG GRAIN TEMP = 13.04 DEG C | PERCENT ABSORPTION = 0.00 H20 REMOVED = 247.82 AVERAGE GRAIN TEMP = 13.04

MC DB	.190	.190	.190	.190	.190	.190	.190	.190	.190	.190	.190
MC WB	.160	.160	.160	.160	.160	.160	.160	.160	.160	.160	.160
TEMP	14.520	13.372	12.965	12.777	12.805	12.819	12.825	12.828	12.829	12.830	12.830
DM LOSS	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070	.070
ABS HUM	.00555	.00581	.00596	.00611	.00616	.00621	.00626	.00631	.00636	.00641	.00646
REL HUM	.52758	.59437	.62600	.64957	.65360	.65829	.66327	.66839	.67358	.67879	.68402
EQUIL MC	.140	.155	.162	.167	.167	.168	.169	.170	.171	.172	.173

TIME =244.00 AVERAGE MC DB = .1895 PERCENT DM LOSS = .071 | PERCENT CONDENSATION = 0.00 AVERAGE MC WB = .1593 OBSEVD AVG GRAIN TEMP = 12.93 DEG C | PERCENT ABSORPTION = 0.00 H20 REMOVED = 249.70 AVERAGE GRAIN TEMP = 12.93

MC DB	.187	.188	.189	.189	.190	.190	.190	.190	.190	.190	.190
MC WB	.158	.158	.159	.159	.160	.160	.160	.160	.160	.160	.160
TEMP	14.520	13.762	13.319	12.896	12.752	12.639	12.555	12.496	12.457	12.433	12.418
DM LOSS	.071	.071	.071	.071	.071	.071	.071	.071	.071	.071	.071
ABS HUM	.00555	.00584	.00599	.00614	.00619	.00624	.00629	.00634	.00639	.00644	.00649
REL HUM	.52758	.58261	.61492	.64780	.65920	.66944	.67848	.68646	.69358	.70009	.70616
EQUIL MC	.140	.152	.159	.166	.168	.170	.172	.173	.175	.176	.177

TIME =248.00 AVERAGE MC DB = .1887 PERCENT DM LOSS = .071 | PERCENT CONDENSATION = 0.00 AVERAGE MC WB = .1588 OBSEVD AVG GRAIN TEMP = 12.92 DEG C | PERCENT ABSORPTION = 0.00 H20 REMOVED = 251.50 AVERAGE GRAIN TEMP = 12.92

MC DB	.184	.186	.188	.188	.190	.190	.190	.190	.190	.190	.190
MC WB	.156	.157	.158	.159	.159	.159	.159	.159	.159	.159	.159
TEMP	14.520	13.825	13.429	13.025	12.868	12.713	12.567	12.436	12.324	12.231	12.157
DM LOSS	.071	.071	.071	.071	.071	.071	.071	.071	.071	.071	.071
ABS HUM	.00555	.00582	.00597	.00612	.00617	.00622	.00627	.00632	.00637	.00642	.00647
REL HUM	.52758	.57856	.60883	.64063	.65247	.66440	.67612	.68735	.69788	.70761	.71654

APPENDIX D - Continued

TIME =272.00
AVERAGE MC DB = .1847
PERCENT DM LOSS = .072

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1559
OBSEVD AVG GRAIN TEMP = 13.19 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 260.71
AVERAGE GRAIN TEMP = 13.19

MC DB	.173	.179	.182	.183	.187	.188	.188	.188	.188	.188	.188
MC WB	.148	.152	.154	.154	.157	.158	.158	.158	.158	.158	.158
TEMP	14.520	14.141	13.756	13.369	13.163	13.020	12.889	12.758	12.625	12.490	12.353
DM LOSS	.072	.072	.072	.072	.072	.072	.072	.072	.072	.072	.072
ABS HUM	.00555	.00570	.00585	.00600	.00605	.00610	.00615	.00620	.00625	.00630	.00635
REL HUM	.52758	.55517	.58402	.61415	.62758	.63867	.64937	.66021	.67131	.68266	.69424
EQUIL MC	.140	.146	.153	.159	.162	.164	.167	.169	.171	.173	.175

TIME =276.00
AVERAGE MC DB = .1841
PERCENT DM LOSS = .072

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1554
OBSEVD AVG GRAIN TEMP = 13.23 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 262.05
AVERAGE GRAIN TEMP = 13.23

MC DB	.172	.178	.182	.182	.187	.187	.187	.187	.187	.187	.187
MC WB	.147	.151	.154	.154	.157	.158	.158	.158	.158	.158	.158
TEMP	14.520	14.144	13.766	13.388	13.252	13.109	12.963	12.817	12.674	12.533	12.394
DM LOSS	.072	.072	.072	.072	.072	.072	.072	.072	.072	.072	.072
ABS HUM	.00555	.00570	.00585	.00600	.00605	.00610	.00615	.00620	.00625	.00630	.00635
REL HUM	.52758	.55506	.58364	.61339	.62395	.63496	.64625	.65769	.66919	.68075	.69238
EQUIL MC	.140	.146	.153	.159	.161	.164	.166	.168	.170	.172	.175

TIME =280.00
AVERAGE MC DB = .1835
PERCENT DM LOSS = .072

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1550
OBSEVD AVG GRAIN TEMP = 13.26 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 263.37
AVERAGE GRAIN TEMP = 13.26

MC DB	.171	.177	.181	.181	.186	.187	.187	.187	.187	.187	.187
MC WB	.146	.151	.153	.153	.157	.158	.158	.158	.158	.158	.158
TEMP	14.520	14.144	13.768	13.454	13.260	13.118	12.988	12.857	12.723	12.585	12.446
DM LOSS	.072	.072	.072	.072	.072	.072	.072	.072	.072	.072	.072
ABS HUM	.00555	.00570	.00585	.00600	.00605	.00610	.00615	.00620	.00625	.00630	.00635
REL HUM	.52758	.55505	.58359	.61076	.62362	.63459	.64520	.65597	.66705	.67841	.69001
EQUIL MC	.140	.146	.153	.159	.161	.164	.166	.168	.170	.172	.174

TIME =281.00
AVERAGE MC DB = .1833
PERCENT DM LOSS = .073

PERCENT CONDENSATION = 0.00
AVERAGE MC WB = .1549
OBSEVD AVG GRAIN TEMP = 13.26 DEG C

PERCENT ABSORPTION = 0.00
H2O REMOVED = 263.70
AVERAGE GRAIN TEMP = 13.26

MC DB	.170	.177	.180	.181	.186	.187	.187	.187	.187	.187	.187
MC WB	.145	.150	.153	.153	.157	.158	.158	.158	.158	.158	.158
TEMP	14.520	14.144	13.768	13.542	13.216	13.105	12.964	12.858	12.727	12.593	12.456
DM LOSS	.073	.073	.073	.073	.073	.073	.073	.073	.073	.073	.073
ABS HUM	.00555	.00570	.00585	.00590	.00605	.00610	.00615	.00620	.00625	.00630	.00635
REL HUM	.52758	.55505	.58359	.59723	.62540	.63510	.64535	.65594	.66685	.67807	.68956
EQUIL MC	.140	.146	.153	.156	.162	.164	.166	.168	.170	.172	.174

APPENDIX E

CONVERSION FACTORS

APPENDIX E

CONVERSION FACTORS

Unit Conversions	English or Metric	SI
Area	1 ft^2	$9.290x10^{-2}m^2$
Convective Heat-Transfer Coefficient	1 BTU/h ft^2 °F	5.678 W/m^2°C
Density	1 lb/ft^3	$1.602x10kg/m^2$
Energy	1 kcal 1 BTU	$4.187x10^3J$ $1.055x10^3J$
Enthalpy, specific	1 BTU/lb	$2.326x10^3J/kg$
Force	1 lbf	4.448 N
Heat Flux	1 kcal/h m^2 1 BTU/h ft^2	1.163 W/m^2 3.155 W/m^2
Heat Release Rate (mass)	1 BTU/h lb	$6.461x10^{-1}W/kg$
Length	1 ft	$3.048x10^{-1}m$
Mass	1 lb 1 tonne 1 ton	$4.536x10^{-1}kg$ $1.000x10^3kg$ $1.016x10^3kg$
Power	1 BTU/h 1 hp	$2.931x10^{-1}W$ $7.457x10^2W$
Pressure	1 standard atmosphere 1 bar 1 lbf/in^2 1 in water 1 mm Hg	$1.013x10^5N/m^2$ $1.000x10^5N/m^2$ $6.895x10^3N/m^2$ $2.491x10^2N/m^2$ $1.333x10^2N/m^2$
Surface per Unit Volume	1 ft^2/ft^3	3.280 m^2/m^3
Specific Heat	1 BTU/lb F	$4.187x10^3J/kgK$
Temperature Difference	1 deg F (deg R)	5/9 deg C (deg K)
Thermal Conductivity	1 BTU/h ft^2 (°F/ft)	1.731 W/m^2 (°C/m)

APPENDIX E, continued:

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