CONCURRENTFLOW DRYING OF GRAIN SORGHUM

AND

THE RESULTING WET MILLING QUALITY

BY

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LIST OF SYMBOLS

a	specific product surface area, m^{-1}
A	constant used in Paulsen and Thompson equation
A	constant
AF	airflow rate, $m^3/s/m^2$
B	constant
C	constant
C	specific heat, KJ/Kg°C
d	differential symbol
D	constant
D	diffusion coefficient, m^2/hr
DAT	drying air temperature, °C
EFF	fuel efficiency, KJ/Kg H_2O
FM	broken and fine content, %
G	mass flow rate (Kg/hr) or Kg/hr m^2
h	convective heat transfer coefficient , KJ/hr m^2 °C
h_{fg}	heat of vaporization (latent heat), KJ/Kg
J	Jindal and Thompson (1972) static pressure symbol
L	bed depth, m
M	local moisture content within kernel, dry basis (decimal)
M	average moisture content, dry basis (decimal)
MC	grain moisture content, % (wet basis)
Me	equilibrium moisture content, dry basis (decimal)
Mo	original moisture content, dry basis (decimal)
MR	moisture ratio, (M-Me)/(Mo-Me)

P	density, Kg/m^3
pt	Paulsen and Thompson (1973) thin layer drying equation
q	energy per unit time, KJ/hr
r	kernel coordinate, m
Rg	dry grain density, Kg/m^3
Rw	wet grain density, Kg/m^3
SP	static pressure, Pa or Pa/m or cm-H_2O
t	time, hour
T	air temperature, °C
V	velocity, m/min or m/s
(Wi-Wo)	loss of water from grain during drying, Kg/hr
Z	intermediate product of Paulsen and Thompson equation
θ	kernel temperature, °C
ϕ	relative humidity, (decimal)

as a subscript

$_a$	air
$_e$	equilibrium
$_H$	Haque et al. (1982) symbol for static pressure
$_i$	imitial
$_o$	at position zero
$_o$	out
$_p$	product
$_t$	at time t
$_v$	vapor
$_w$	water

as an abbreviation

AE	air equation
ave	average
bu	bushel
CC/CF	concurrent counterflow
CCF	concurrentflow
CF	crossflow
CFM	cubic feet per minute
DAT	drying air temperature
d.b.	dry basis
GFT	grainflow tube
LHE	latent heat equation
M.C.	moisture content
M.T.	metric tonne
Temp	temperature
ton	tonne
U.S.	United States
w.b.	wet basis

ABSTRACT

CONCURRENTFLOW DRYING OF GRAIN SORGHUM

AND

THE RESULTING WET MILLING QUALITY

By

GARRET FEDEWA

A pilot-scale concurrent/counterflow (CC/CF) dryer was determined to have a fuel efficiency of approximately 4950 KJ/Kg in reducing grain sorghum from a M.C. of 16.0 to 12.5% w.b. at drying air temperatures of about 200-220°C. CC/CF drying was generally more fuel efficient at the high drying air temperatures and less fuel efficient at the low final moisture contents.

A simulation model predicted acceptable results compared to the experimental results. A CC/CF sorghum dryer can reduce 16% M.C. sorghum to a safe storage M.C. (11 - 12% w.b.) at drying air temperatures as high as 215°C (420°F) without affecting the wet milling quality; starch yield and protein content in the starch were found to be acceptable in the CCF dried grain sorghum.

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DATE May 14, 1985

APPROVED Donald M. Edwards
Department Chairman

DATE May 14, 1985

CHAPTER 1

INTRODUCTION

The Arab-Sudanese Starch and Glucose Company in Khartoum, Sudan purchased a 12' x 12' three-stage concurrent/counterflow (CC/CF) sorghum dryer from Blount, Inc., Montgomery, AL. The CCF dryer was erected in 1983/84 and is expected to be placed in operation in 1985. The dryer is designed to dry grain sorghum to a safe storage moisture content (10-11% w.b.) at a wet milling starch factory. The starch is to be used for human consumption. This thesis is concerned with the CCF dryer performance and its effect on the wet milling characteristics of concurrentflow (CCF) dried grain sorghum.

A pilot-scale concurrent/counterflow (CC/CF) dryer was used to determine the drying parameters, the energy efficiencies, and the wet milling quality (starch yield and protein in the starch) of CCF dried grain sorghum. The pilot-scale testing took place at the Blount/mfs (Modern Farms Systems, Inc.) facility in Grand Island, NE in November of 1983. The experimental data was utilized in verifying a simulation model. The model was developed at the Agricultural Engineering Department, Michigan State University, East Lansing, MI and was used to design a CC/CF dryer for the Arab-Sudanese Starch and Glucose Company (Bakker-Arkema et al., 1983a). Samples of CCF dried grain sorghum were analyzed for USDA grade, germination and wet milling quality.

1.1 UNITS

Throughout this thesis SI units are used. Conversion factors from SI to English units are given in Appendix A. All bushel conversions use a 58 pound bushel. All ton designations are metric tons.

CHAPTER 2

BACKGROUND

The origin of the name "sorghum" is obscure. In medieval Latin it appears to have been known as "surgo", and may therefore have been derived from the Latin verb "surgere" meaning "to rise" (Hulse, et al., 1980). Sorghum is a member of the Gramineae family and the tribe Andropogoneae. The sorghums of commercial importance are called Sorghum bicolor (L.) Moench (Rooney, 1973).

The greatest variability in both the cultivated and the wild sorghums is found in the north-east quadrant of Africa (Doggett, 1970). It is commonly believed that sorghum originated in Ethiopia.

The Sorghum bicolor types have been divided into four major categories: (1) forage or sweet sorghum; (2) grassy sorghum; (3) broomcorn; and (4) grain sorghum.

2.1 FORAGE AND SWEET SORGHUM

Sweet sorghum is believed to have been one of the earliest domesticated plants, grown by the Egyptians in 2200 BC (Ahlgren, 1949). Sweet sorghum was introduced into the United States (U.S.) in 1853 (Cundiff and Parrish, 1983). The crop is used as a forage and silage (Quinby and Marion, 1960), and for the production of table syrup, ethanol and raw sugar (Smith, 1982). The drying of sweet sorghum stalks for storage appears to be impractical because of the high energy requirements (Cundiff and Parrish, 1983).

2.2 GRASSY SORGHUM AND BROOMCORN

The grassy types of sorghum have thin stems, narrow leaves, numerous tillers, and small spikelets and seeds. They are useful for hay and grazing (Martin, 1970). Sudangrass and johnsongrass are two common types.

Broomcorn has long panicle branches which are used for the production of brooms (Rooney, 1973). Benjamin Franklin is credited with the introduction of broomcorn into the U.S. from England in 1725 (Weibel, 1970). In 1942, forty-thousand tons of broomcorn were produced in the United States. Today broomcorn production has dwindled due to labor costs.

2.3 GRAIN SORGHUM

World grain sorghum (Sorghum bicolor (L.) Moench) production ranks fifth among the major cereal crops. The order of the five major cereals crops is: rice, wheat, corn, barley and grain sorghum (Rooney et al., 1982). Grain sorghum is grown mainly in hot, dry regions where corn cannot be successfully produced. Major production areas in the world are the southwestern U.S., India, Africa, Argentina, and Mexico (see Table 2.3). Of the total world production, over 50% is used directly for human food, mainly in Asia and Africa (Rooney et al., 1982).

Grain sorghum is called by many other names, some of which are: milo, sorghum grain, milo maize, hegari, kafir-corn, kafir, guinea corn, gyp corn, rice corn, Egyptian rice, Jerusalem corn, Cholam, Jowar, Juar, the great millet, durra, kaoling, feterita, and others (Rooney et al., 1982). In this thesis, grain sorghum is referred to as sorghum.

The U.S. is the largest producer and exporter of grain sorghum and uses it almost entirely as an animal feed grain. In the 1982/1983 season the U.S. produced 22.1 million metric tons (841 million bushels) of which 6.3 million metric tons (240 million bushels) were exported. The average yield was 1.552 metric tons (59 bushels) per acre and the season average farm price was $92.29 per metric ton ($2.47 per bushel) (Bakker-Arkema et al., 1983a).

Taylor et al. (1979) reported that 95% of the grain sorghum grown in the U.S. for export passes through the Gulf ports. This was due to proximity to the grain sorghum producing areas in Texas, Kansas, Nebraska, and Oklahoma. Jackson et al. (1980) have given an extensive report on the U.S. Sorghum Industry.

TABLE 2.3 GRAIN SORGHUM PRODUCTION IN 1976 (HULSE ET AL., 1980)

	AREA HARVESTED (10^3ha)	YIELD (kg/ha)	PRODUCTION (10^3 metric ton)
WORLD	43929	1179	51812
AFRICA	13939	704	9813
MEXICO	1180(U)*	2839	3350(U)
U.S.	6020	3053	18382
ARGENTINA	1834	2835	5200(U)
ASIA	18956	591	11202
INDIA	16000(F)**	544	8700(F)

*U = UNOFFICIAL FIGURE

**F = FAO (Food and Agricultural Organization of the United Nations) estimate

2.3.1 USDA GRAIN STANDARDS

The USDA (United States Department of Agriculture) has defined the following classes of sorghum (based on color): (1) brown sorghum; (2) white sorghum; (3) yellow sorghum, and (4) mixed sorghum (USDA, 1974). The source of pigment may be the pericarp or subcoat (seedcoat or testa). Yellow sorghum is the major type of grain produced in the U.S. This class may contain yellow, salmon-pink, red, or white pericarps, or white with spotted pericarps. The pigments other than yellow or white are a source of irritation for the wet-miller because bleaching is required to produce a consistent and acceptable product. Rooney et al. (1970) suggested changing the yellow class to red and creating a true yellow endosperm class.

The U.S. grading standards (Table 2.3.1a) of sorghum are based on measurements of density (pounds per bushel), M.C. w.b., heat-damaged and broken kernels, foreign material and other grains (USDA, 1974). A round sieve of 0.000992m (0.03906 inch) is used to remove the dockage from a sample. The standards apply to all classes. The grade is determined by the property that qualifies for the lowest grade. The grading system allows for a substantially higher percentage of BCFM than is allowed in corn of similar grade (Table 2.3.1b). For example, grade 3 allows 12% BCFM in sorghum but only 4% BCFM in corn. Sorghum requires greater cleaning and has a lower starch yield per bushel than corn because of BCFM differences.

TABLE 2.3.1a

GRADES, GRADE REQUIREMENTS, AND GRADE DESIGNATIONS

Sec. 26.557 Grades and grade requirements for all classes of sorghum

	Maximum limits of --				
GRADE	Minimum test weight per bushel	Moisture	Damaged kernels: Total	Damaged kernels: Heat damaged kernels	Broken kernels, foreign material & other grains
	Pounds	Percent	Percent	Percent	Percent
U.S. No. 1	57.0	13.0	2.0	0.2	4.0
U.S. No. 2	55.0	14.0	5.0	0.5	8.0
U.S. No. 3	53.0	15.0	10.0	1.0	12.0
U.S. No. 4	51.0	18.0	15.0	3.0	15.0
U.S. Sample grade	U.S. Sample grade shall be sorghum which (a) Does not meet the requirements for-- the grades U.S. Nos. 1,2,3, or 4. (b) Contains more than 7 stones which have an agregate weight in excess of 0.2 percent of the sample weight or more than 2 crotalaria seeds (Crotalaria spp) per 1,000 grams of sorghum. (c) Has a musty, sour, or commercially objectionable foreign odor (except smut odor) or (d) Is badly weathered, heating, of distinctly low quality (see Sec. 26.552(d).				

Sorghum which is distinctly discolored shall not be graded higher than U.S. No. 3

(USDA, 1974)

TABLE 2.3.1b

NUMERICAL GRADES AND SAMPLE GRADE REQUIREMENTS FOR CORN
Includes the Classes Yellow Corn, White Corn and Mixed Corn

		Maximum Limits			
				Damaged Kernels	
Grade	Minimum Test Weight Per Bushel Lb	Moisture %	Broken Corn and Foreign Material %	Total %	Heat-Damaged Kernels %
1	56	14.0	2.0	3.0	0.1
2	54	15.5	3.0	5.0	.2
3	52	17.5	4.0	7.0	.5
4	49	20.0	5.0	10.0	1.0
5	46	23.0	7.0	15.0	3.0
Sample Grade	Sample grade shall be corn which does not meet the requirements for any of the grades from No. 1 to No. 5, inclusive, or which contains stones, or which is musty, or sour, or heating, or which has any commercially objectionable foreign odor, or which is otherwise of distinctly low quality.				

(Brooker et al., 1974)

2.3.2 SOME FIELD, HARVESTING AND STORAGE CHARACTERISTICS

Sorghum performs best under favorable moisture, temperature, and humidity conditions. However, it is usually grown in dry, hot areas where corn is unable to grow. Successful production requires a mean summer temperature of 18.3°C (65°F) with at least 120 frost-free days (Watson, 1967). Drought resistance of sorghum is attributed to: (1) the xerophytic leaf characteristics that retard water loss (Wall and Ross, 1970); (2) the ability to remain dormant during a drought period (Doggett, 1970); and (3) the secondary root structure which is twice that of corn (Miller, 1916).

The sorghum crop is known to depress certain crops following it. It can depress growth by depleting the soil of moisture and nutrients (nitrogen) (Wall and Ross, 1970). Plant residues may have toxic effects (Guenzi et al., 1967). Common rotations to restore the soil are sorghum-fallow-wheat and sorghum-soybeans-cotton.

Sorghum is normally harvested at 14-18% moisture content wet basis (w.b.) with standard combines (Watson, 1967). Fairbanks (1979) reported that the total harvesting losses at 20-30% moisture content w.b. are sufficiently high to discourage early harvest even at optimum cylinder speed and cylinder-concave clearance adjustments.

The quality of stored sorghum is directly related to the M.C., temperature and length of time (Bass and Stanwood, 1978).

Brooker et al. (1974) recommended a 12-13% moisture content for one year of safe storage and a moisture content of 10-11% for up to 5 years storage. Sorsenson et al. (1957) reported that for South Texas: (1) sorghum with a moisture content (M.C.) higher than 14% does not store satisfactorily; (2) the maximum M.C. for safe storage is 12% in order to retain market value or to store over one year with regular turning or aeration; (3) excessive trash can cause heating in bins with sorghum at 11-12% M.C.; (4) storage of sorghum for longer than one year without turning or aeration requires limiting the M.C. to 11% or less; and (5) sorghum at 12 to 14% M.C., which is aerated or turned during storage, can be stored safely for nine months.

In the 1960's several papers on the storage of sorghum were written by researchers at the Texas Agricultural Experimental Station. Among the topics researched were: (1) operating costs (Bonnen and Cunningham, 1965); (2) commercial storage and handling (Moore and Brown, 1965); (3) on farm storage and disposal (Brown and Moore (1965); and (4) the use of conditioned air (Person et al., 1967).

Whitney and Petersen (1961) found that insects become inactive and die at 10°-15.5°C (50-60°F). Relative humidities below 60% usually eliminate molds (Brooker et al., 1974). Haile and Sorenson (1968) showed that the respiration of stored sorghum aerated at a rate of 0.107m^3/min/ton (0.1 cubic feet per minute (CFM) per bushel) increases at an accelerating rate when the grain M.C. is above

15% and the temperature is above 15.5°C (60°F). Aeration systems with airflow rates of 0.054 - 0.107 m^3/min/ton (.05 - .1 CFM/bu) are used to maintain the quality of the grain.

Sorensen and Person (1970) reported that resistance to the flow of air depends on: (1) the type of grain; (2) the storage depth; (3) the amount of foreign material; (4) the grain M.C.; (5) the compaction; and (6) the airflow rate. Shedd et al. (1953) reported data for resistance to air flow of packed and loose sorghum. Chung et al. (1984) developed an empirical equation to determine the static pressure from the amount of fine material, M.C., and airflow. The equation developed is:

$$SP = A(AF) + B(AF)^2 - C(MC)(AF) + D(FM)(AF)$$

WHERE

SP = pressure drop per meter depth of grain, Pa/m

AF = airflow rate, $m^3/s\ m^2$

MC = grain moisture content, % (w.b.)

FM = broken and fine content, %

A,B,C,D = constants A = 4590.59 B = 7732.24 C = 192.44 D = 196.76

2.3.3 STRUCTURE, COMPOSITION AND PROPERTIES

The sorghum plant resembles corn in vegetative appearance. Sorghum varieties range from 0.61 to 4m (2 to 15 ft.) in height and have an average of 10 to 16 broad leaves on a stiff stalk (Watson, 1967). The grain is carried on a terminal head, or rachis, containing 800-3000 kernels.

The sorghum kernel is a flattened sphere approximately 4.0mm long by 3.5mm wide by 2.5mm thick. The sorghum seed is a caryopsis which is a dry fruit with a single seed enclosed in a dry outer covering which is fused to the seedcoat. The major portions of the kernel are the outer covering (pericarp), the storage tissue (endosperm) and the germ or embryo. The endosperm, germ and pericarp compromise 80.0 - 84.6%, 7.8 - 12.1%, and 7.3 - 9.3% of the whole kernel dry weight (Rooney, 1973).

Figure 2.3.3 shows the structural portion of the sorghum kernel. The pericarp is made up of four different parts: the epicarp, the mesocarp, the cross cells, and the tube cells. The seedcoat (testa, subcoat or undercoat) is adjacent to the inner integument. The seedcoat is not present in all grains and it may or may not be pigmented. The embryo (germ) is firmly embedded in the kernel and is smaller and more difficult to remove than the germ of corn (Rooney, 1973). The endosperm is composed of the aleurone layer and the peripheral, corneous (hard, flinty or horny) and floury areas. The endosperm cells are high in protein, fat, minerals and enzymatic activity.

Grain sorghum generally is lower in fat content, but slightly higher in protein and starch content than corn. Tables 2.3.3a and 2.3.3b give an approximate composition of sorghum (Rooney and Clark, 1968).

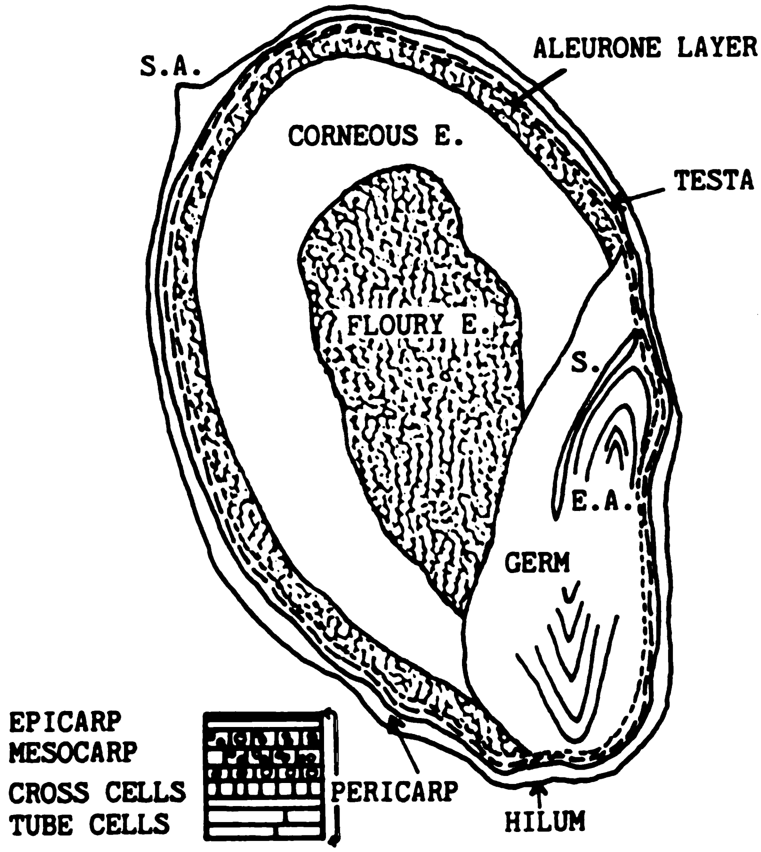

Figure 2.3.3 Structural portions of the sorghum kernel (Hoseney et al., 1981).

Composition is mostly determined by genetic and environmental factors. Type of soil, amount of rainfall, and weather are considered the main environmental factors.

Corn and sorghum starch look microscopically identical, although sorghum starch is slightly larger in diameter than corn starch (Watson, 1960). There are two major groups of sorghum starch, regular and waxy. Regular starch contains approximately 25% amylose, the linear starch component, and 75% amylopectin, the branched starch component. Waxy starch contains approximately 100% amylopectin. The gelatinization temperature range of regular starch is 64°C - 74°C (147°F - 165°F); for waxy starch 66°C - 76°C (151°F - 169°F) (Watson, 1970). Corn starch has a gelatinization range of 62°C - 72°C (144°F - 162°F) (Otterbacher and Kite, 1958). Therefore, sorghum starch gelatinization is less energy efficient than corn starch gelatinization. Hoseney et al., (1981) reported that (1) sorghum starch content in cultivars ranges from 32 to 79%; (2) waxy sorghums tends to have lower starch content than nonwaxy cultivars; (3) gelatinization temperature ranges are affected by amylose/amylopectin ratios; (4) at the same starch content concentration, waxy starches produce higher peak viscosities, greater thinning during cooking, and less setback during cooling, than the nonwaxy counterparts; and (5) sorghum starch granules are polygonal or spherical and ranged from 4 to 24 micrometers.

TABLE 2.3.3a

COMPONENT PARTS OF SORGHUM KERNELS AND PROXIMATE ANALYSIS

		Proportion of Kernels %	Composition of Kernel Parts Starch % d.b.	Protein % d.b.	Fat % d.b.	Ash % d.b.
Whole kernel	Mean		73.8	12.3	3.6	1.65
	Range		72.3-75.1	11.5-13.2	3.2-3.9	1.57-1.68
Endosperm	Mean	82.3	82.5	12.3	0.6	0.37
	Range	80.0-84.6	81.3-83.0	11.2-13.0	0.4-0.8	0.30-0.44
Bran	Mean	7.9	34.6	6.7	4.9	2.02
	Range	7.3-9.3		5.2-7.6	3.7-6.0	
Germ	Mean	9.8	13.4	18.9	28.1	10.36
	Range	7.8-12.1		18.0-19.2	26.9-30.6	

(Rooney and Clark, 1968)

TABLE 2.3.3b

PROXIMATE ANALYSIS OF SORGHUM GRAINS

	Range	Average
Moisture	8-20	15.5
Starch	60-77	74.1
Protein (N x 6.25)	6.6-16.0	11.2
Fat	1.4-6.1	3.7
Ash	1.2-7.1	1.5
Crude Fiber	0.4-13.4	2.6
Sugars (dextrose)	0.4-2.5	1.8
Tannin	0.003-0.17	0.1
Wax	0.2-0.5	0.3
NFE	65.3-85.3	
Penlosans	1.8-4.9	2.5

(Rooney and Clark, 1968)

Jambunathan et al. (1983) stated that protein quality of sorghum is lowest among the cereals, mainly because of its low levels of lysine. Hoseney et al. (1981) reported that: (1) protein content of sorghum varies widely (6 to 25%); (2) lysine frequently appears to be the first limiting amino acid; and (3) sorghum is usually high in glutamic acid, leucine, alanine, proline, and aspartic acid (see Table 2.3.3c). A more balanced amino acid composition is being sought in sorghum to improve its nutritional value (Rooney et al., 1970).

Germ oil and sugars in sorghum are similar to corn (Watson, 1967). The oil content of sorghum is about 1% lower than corn oil (Watson, 1960) as is illustrated in Table 2.3.3d. Recent reviews of the composition of sorghum were made by Hulse et al. (1980) and Hoseney et al. (1981).

Zink (1935) found the specific gravity of sorghum to be 1.22 and the void spaces in bulk to be 37%. Stahl (1950) reported the angle of repose for emptying or funneling to be 33°, and for filling and piling to be 20°. Sharma and Thompson (1973) developed the following equation for thermal conductivity (K):

$$K = 0.0564 + 0.000858M$$

Where:

K = thermal conductivity, BTU/h-Ft-°F
M = M.C. (w.b.)
R = 0.955, correlation coeffecient
S = 0.00173 standard error of estimate

Average surface areas are: (1) White Kafar grain sorghum, 0.3363 cm^2, (Fan et al., 1963); (2) Atlas Sorgo sorghum, 0.3193 cm^2, (Fan et al., 1963); and (3) Red grain sorghum, 0.7238-0.9852 cm^2 (Suarez et al., 1980). The bulk density is 717.6 Kg/m^3 (44.8 lb/Ft^3) at 13-14% M.C. (w.b.) (Brooker et al., 1974). Rooney and Clark (1968) found the average kernel weight to be 28 mg and to vary from 5 to 50 mg. Watson (1967) reported 26,500 - 35,300 seeds per kilogram (12,000 to 16,000 seeds per pound).

2.4 WET MILLING SORGHUM AND UTILIZATION OF PRODUCTS

Hightower (1949) reported the first commercial wet milling plant designed specifically for sorghum. It was built by Corn Products Refining Co. in Corpus Christi, TX. Dextrose, starch, animal feed and edible oils were produced. In the U.S. 149.7 - 199.6 million Kg (six - eight million bushels) were wet milled between 1950 and 1970 (Rooney, 1973). However in 1973, wet milling was discontinued. The reasons for discontinuing wet milling in the U.S. were fivefold:

(1) The price of sorghum became noncompetitive with corn (Rooney et al., 1973).

(2) Sorghum starch yields are technically more difficult to obtain than corn starch yields. This is primarily due to a difference in size, a larger horny endosperm area in sorghum than in corn and a layer of dense cells

TABLE 2.3.3c

REPORTED AMINO ACID COMPOSITION OF SORGHUM
(g/100 g of protein)

	Reference			
	Waggle et al. 1967	Jones and Beck with 1970	Jambunathan and Mertz 1973	Hoseny et al. 1974
Lysine	2.08	1.8	2.14	2.24
Histidine	2.23	2.1	2.01	1.71
Ammonia		3.3		2.95
Arginine	3.32	3.2	3.59	3.18
Aspartic acid	6.87	7.0	7.83	6.94
Threonine	3.10	3.5	3.26	3.64
Serine	4.34	4.6	4.52	4.73
Glutamic acid	22.40	24.9	23.22	22.27
Proline	8.27	9.0	8.16	7.19
Glycine	3.10	3.2	3.07	3.40
Alanine	9.85	9.9	9.89	9.11
Half-cystine	1.56	0.7	0.92	1.73
Valine	5.25	4.9	5.35	4.51
Methionine	1.17	1.3	1.03	1.23
Isoleucine	4.24	3.9	4.08	3.77
Leucine	14.36	14.5	14.27	13.11
Tyrosine	2.14	4.6	4.50	3.41
Phenylalanine	5.30	5.3	5.19	4.89

(Hosney et al., 1981)

TABLE 2.3.3d

COMPARATIVE COMPOSITION OF CORN AND GRAIN SORGHUM

Component % d.b.	Grain Sorghum (a)	Yellow Dent (Corn (b)
Starch	71.1	72.1
Protein (N x 6.25)	12.8	9.5
Fat	3.7	4.6
Ash	1.5	1.4
Tannin	0.01	None
Wax	0.4	0.03
Carotenoid Pigments, ppm	None	15.30

(a) Average values for major components analyzed in grain received over a 3 1/2 year period at Corpus Christi, TX.

(b) Average values for major components analyzed in corn received over a 3 1/2 year period at Pekin, IL.

(Watson, 1960)

rich in protein at the periphery of the endosperm just inside the aleurone layer (Watson et al., 1955). Hubbard et al. (1950) found that the pericarp cannot be completely removed from the kernel even when soaked. This results in a small amount of pericarp material attached to the endosperm. Freeman and Watson (1969) peeled the pericarp fragment from the endosperm. They obtained a whiter starch product, lower protein content in the starch, increased yield and purity of the germ, and a higher wax recovery. However, they also observed that starch losses during peeling negated the above.

(3) Bleaching is an additional cost because pigments discolor the starch product.

(4) Some sorghum types have a brittle pigmented subcoat which leaves fragments in the starch product.

(5) Grain standards allow more BCFM in sorghum than BCFM in corn. This results in costly cleaning and loss of product.

Watson et al. (1955) reported that starch purification and recovery from sorghum are more difficult than from corn. This is because of a larger portion of horny endosperm and a layer of dense cells rich in protein at the periphery of the endosperm just inside the aleurone layer. A microscopic examination revealed protein matrices encasing starch granules in the endosperm which lowered starch yields and increased protein starch content. Starch is more readily released in the floury endosperm than the horny endosperm because of fewer protein matrices (Watson and Hirata, 1954).

The purpose of wet milling is to obtain a pure, complete separation of the component parts. Products are starch, oil and feed. Sorghum and corn are wet milled similarly (Watson, 1967).Figure 2.4 presents a commercial wet milling flow diagram. Wet milling involves (Watson, 1970):

(1) cleaning the grain of undesirable material;

(2) steeping the grain for 40-50 hrs. in 0.20 - 0.25% SO_2 water at 50 - 52°C;

(3) milling the grain to obtain as pure a separation of the component parts as possible;

(4) and then recovery of the component parts for suitable processing.

Cox et al. (1944) found that SO_2 facilitates gradual swelling of the protein matrix in the germ and endosperm and allows the release of entrapped starch granules. Zipf et al. (1950) found that when steepwater contains less than 0.20% SO_2, germ separation was impaired. About 7.0 - 7.5% dry solid matter becomes soluble in the steepwater. The steeping temperature discourages the growth of yeast and putrefactive organisms but encourages lactic acid bacteria development. Lactic acid bacteria lower the steepwater pH and soften the kernel with lactic acid production. The kernel has a M.C. of about 45% w.b. after steeping. Watson and Hirata (1962) found that corn artificially dried at excessive temperatures (above 140°F (60°C)) attains a lower final M.C. than 45% w.b.

Table 2.4a shows laboratory wet milling results of three types of sorghum. Variations in yield are common between different kinds of sorghum (Watson, 1970). Table 2.4b shows laboratory wet milling yields obtained with regular and high-oil dent corn, and with regular red milo. Starch yields and oil yields are usually higher for corn than for sorghum.

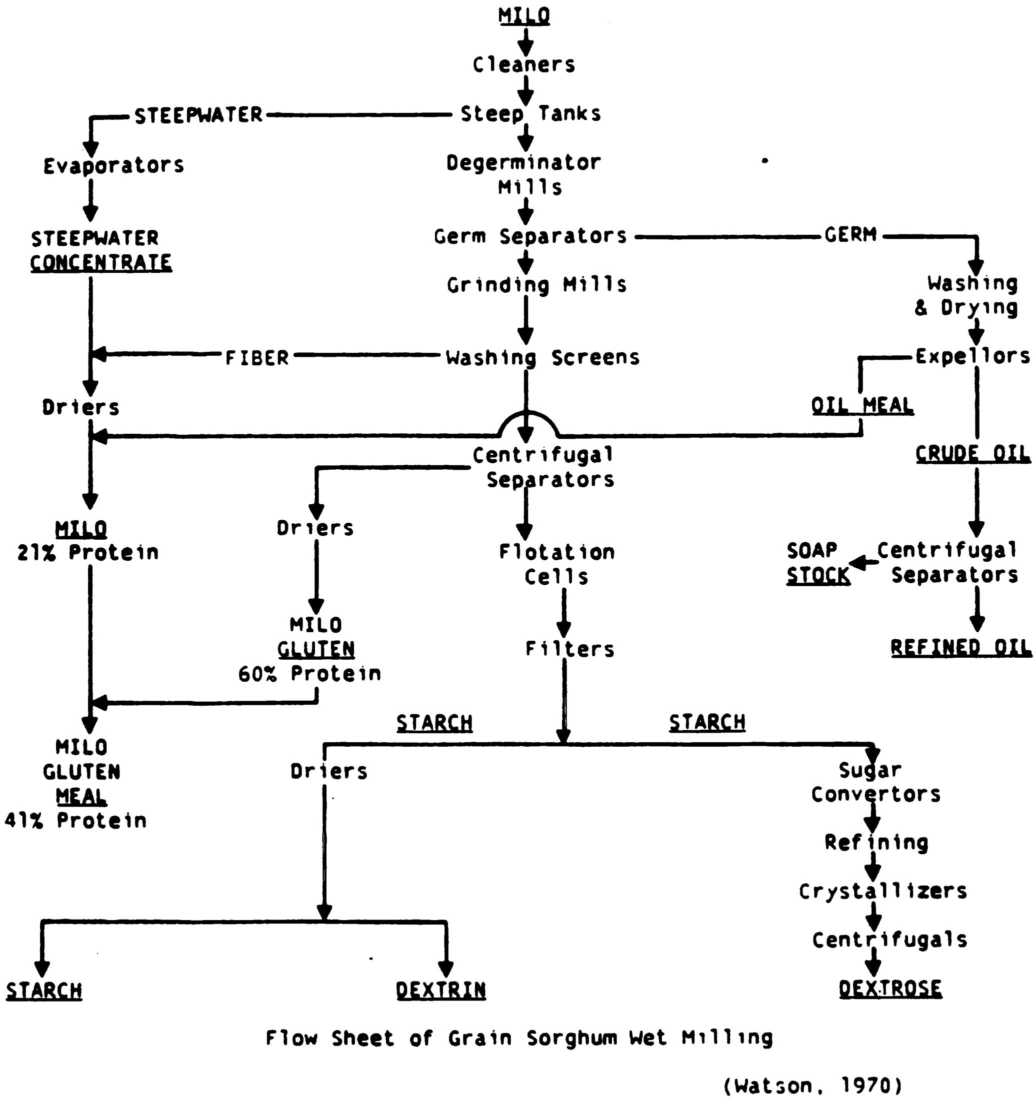

Figure 2.4 Flow sheet of grain sorghum wet milling (Watson, 1970).

TABLE 2.4a

Laboratory Wet Milling Results for 3 Types of Grain Sorghum

	Regular Red (Commercial)	Waxy (White)	Yellow Endosperm[6]
Whole Grain Analysis			
Moisture	14.5	13.5	14.0
Starch[1]	73.1	71.9	74.8
Protein	12.1	11.4	10.3
Fat, total[2]	3.6	4.1	3.3
Wax	0.3	0.3	
Xanthophyll,ppm	1	1	5.8
Solubles			
Yield[3]	6.9	7.6	7.4
Protein	48.2	45.8	46.2
Table Starch			
Yield	64.2	61.3	67.9
Protein[4]	0.3	0.2	0.4
Fat (total)[5]	0.7	0.1	
Germ			
Yield	6.2	5.9	4.0
Starch	18.6	10.8	16.6
Protein	11.8	10.3	15.0
Fat	38.8	42.6	43.4
Oil yield[3]	2.4	2.5	1.7
Fiber			
Yield	8.2	9.0	7.7
Starch	30.6	35.4	22.2
Protein	23.2	21.3	15.7
Fat	2.4	3.7	7.0
Table Gluten			
Yield	10.6	11.0	9.2
Starch	42.8	41.9	31.6
Protein	46.7	40.9	50.3
Fat	7.9	8.7	9.9
Xanthophyll, ppm			16.0
Middlings			
Yield	1.2	2.0	1.6
Total dry substance recovery	97.0	96.8	97.8

[1] % dry basis.
[2] Includes Wax.
[3] % of original grain, dry basis.
[4] Analytical values expressed as % of fraction, dry basis.
[5] Determined by acid hydrolysis.
[6] DeKalb Hybrid G600.

(Watson, 1970)

TABLE 2.4b

Laboratory Wet Milling Results Obtained with Regular and High-oil Dent Corn and Regular Red Milo[a]

Fraction	Regular dent corn (%)	High-oil dent corn (%)	Red milo (%)
Whole grain analysis			
Moisture	14.3	13.6	14.9
Starch	71.5	67.0	73.1
Protein	10.5	10.4	13.0
Fat	5.10	7.96	3.6
Wax	Trace	Trace	0.32
Solubles			
Yield[b]	7.6	10.8	7.20
Protein[c]	46.1	46.9	41.5
Starch			
Yield	63.7	59.7	60.17
Protein	0.30	0.26	0.32
Fat	0.02	0.03	0.03
Germ			
Yield	7.3	10.9	6.17
Starch	7.6	7.2	19.1
Protein	10.7	7.2	11.9
Fat	58.9	65.5	39.6
Oil Yield[b]	4.30	7.14	2.44
Fiber			
Yield	9.5	9.8	9.30
Starch	11.4	12.3	36.7
Protein	11.3	11.0	19.7
Fat	1.8	2.7	3.8
Gluten			
Yield	7.4	6.3	9.57
Starch	25.8	32.0	39.9
Protein	50.7	42.3	47.2
Fat	3.7	4.4	5.4
Squeegee			
Yield	3.9	3.6	5.57
Starch	91.7	93.8	74.8
Protein	6.1	3.6	20.7
Fat	0.3	0.4	1.6
Total dry substance	99.4	101.0	98.0

[a] All percentages other than moisture are expressed on a dry basis.
[b] Percent of original grain.
[c] Analytical values expressed as percent of the fraction.

(Watson, 1967)

Sorghum starch (60-70% recovery) is almost identical with corn starch in properties and therefore is useful in the same ways. Various uses are: (1) paper products; (2) textiles; (3) adhesives; (4) drilling muds; (5) baking, confections, brewers' grits, and other foods; (6) explosives; and (7) building materials. Hoseney et al. (1981) and Hulse et al. (1980) published excellent reviews on the international uses of sorghum.

The recovery of oil and feed products are 2 - 3% and 22 - 38% during wet milling, respectively . Sorghum oil is similar to corn oil and is excellent for cooking and salad use. Corn feed products are considered of higher quality because they contain xanthophyll. Xanthophyll produces a desirable yellow color for broiler poultry (Watson, 1960).

CHAPTER 3

GRAIN DRYING

This thesis is primarily concerned with drying sorghum with a concurrentflow (CCF) dryer. However, there are many different grain drying systems capable of drying sorghum. Initial cost, capacity, grain quality and energy efficiency will be considered as criteria. The CCF dryer is the last subject of this section. Solar and heat pump drying units are not discussed because they are unable to compete economically with conventional drying systems (Kranzler et al., 1980; and Hogan et al., 1983).

3.1 BATCH DRYERS

Four types of batch drying systems will be discussed. They are low-temperature in-bin drying, batch-in-bin drying, continuous in-bin counterflow drying and column batch drying systems.

Grain-drying systems generally include an air device, a means of introducing the air into the grain mass, and a chamber to hold the grain. Grain dryers may be either batch or continuous flow in design.

Batch drying systems are either in-bin or column type. Examples of continuous flow systems are: crossflow, concurrentflow, and mixed-flow dryers. Dryers can further be classified with respect to capacity, operating temperature range and direction of airflow relative to grain.

3.1.1 LOW-TEMPERATURE IN-BIN DRYING SYSTEMS

Low temperature in-bin drying systems have a low capacity, low initial cost, low energy consumption, and produces grain of excellent quality (virtually no heat damage and few stress cracks). The units require careful management to prevent mold development. The humidity should be below 55% and the average daily temperature below 10°C (50°F) (Brook, 1979a). Airflow rates vary from 0.54 m^3/min/ton to 5.38 m^3/min/ton (0.5 - 5.0 CFM/bu). Mittal and Otten (1979) concluded that in Ontario, Canada a control system was required to minimize the energy usage in a low temperature drying system. The recommended minimum airflow rate and the maximum bin depth depend on the initial MC and on the environmental conditions (Pierce and Thompson, 1979). Kalchik et al. (1979) found that the natural air drying system (Table 3.1.1) is more energy efficient than the low-temperature, in-bin drieration, in-bin counterflow and automatic drying batch systems.

Table 3.1.1

Standardized energy consumption for five alternative combination drying methods in Michigan, U.S.A. (43°N latitude)

Drying Technique	Electricity* kWh/ha	Propane l/ha	Energy efficiency kJ/kg	Total energy+ propane equiv l/ha
Natural air' (26-23-15.5%)m.c.	3430	729	3227	1216
Low-temperature' (26-23-15.5%)m.c.	4819	729	3756	1411
In-bin direration' (26-20-15.5%)m.c.	944	1421	4140	1552
In-bin counterflow (26-18-15.5%)m.c.	1035	1562	4548	1710
Automatic batch (26-12.5%)m.c.	334	2879	6589	2926

*Based on 62.5 t initial m.c.26-0% (w.b.) final m.c. 15.5%
+Based on 6.0 t/ha
'Energy efficiency of high-temperature drying phase is 6228 kJ/Kg H_2O

(Kalchik et al., 1979)

3.1.2 BATCH-IN-BIN DRYING

Batch-in-bin drying systems have a moderate initial cost and energy consumption. The seasonal capacity is usually between 210 to 395 MT (8,000 to 15,000 bushels) (Brook, 1979b). The quality of the grain is relatively low because of over-drying of the bottom layers in the bin. The airflow rate is 10.76 - 26.91 m^3/min/ton (10 - 25 CFM/bu) with an operating temperature between 38°C (100°F) and 71°C (160°F). A uniform filling in the bin (usually 0.91m (3 ft.) to 1.2m (4 ft.)) is essential for producing an even airflow through the grain. Drying is stopped before the grain layers in the top of the bin are at a safe storage M.C. and the entire batch is mixed to produce a safe storage M.C. This results in a nonuniform grain mixture with some grain over-dried and some grain under-dried.

Stirring devices are often used with low temperature and batch-in-bin drying systems. Stirring offers the following advantages:

(1) reduced moisture gradients in the grain mass,

(2) increased airflow rate,

(3) increased drying rate proportional to the increased airflow rate,

(4) the breakup of wet pockets of grain that may have formed in the drying process (Brooker et al., 1974).

Bridges et al. (1984) suggested that stirring devices are best used with in-bin drying systems running near 100% drying capacity.

3.1.3 CONTINUOUS IN-BIN COUNTERFLOW DRYING

A continuous in-bin counterflow drying system removes the grain by layers (10.0-15.0 cm) as it dries from the bottom with a tapered sweep auger. As grain is removed, grain can be added to the top. This results in less overdrying of the grain.

This system is higher in initial cost and drying capacity than the batch-in-bin system. Bakker-Arkema et al. (1980) found the continuous in-bin counterflow drying system to be energy efficient and reliable.

The airflow rate is from 10 to 30 m^3/min/ton (9.3 - 27.9 CFM/bu). The operating temperatures range from 60°C to 90°C (Bridges et al., 1983).

3.1.4 COLUMN BATCH DRYERS

Column batch dryers (Figure 3.1.4) operate with a stationary bed of crossflow design. The column thickness is usually 0.3m (12 in) with an airflow rate of 75.3 - 96.9 m^3/min/ton (70 - 90 CFM/bu) and drying air temperatures up to 110°C. These dryers are moderately expensive. The capacity can be as high as 1580 metric tons per season (60,000 bu) (Brook, 1979b). The grain quality is usually reduced due to the severe drying treatment and the resulting stress cracks. Kalchik et al. (1979) reported that the automatic batch dryer is

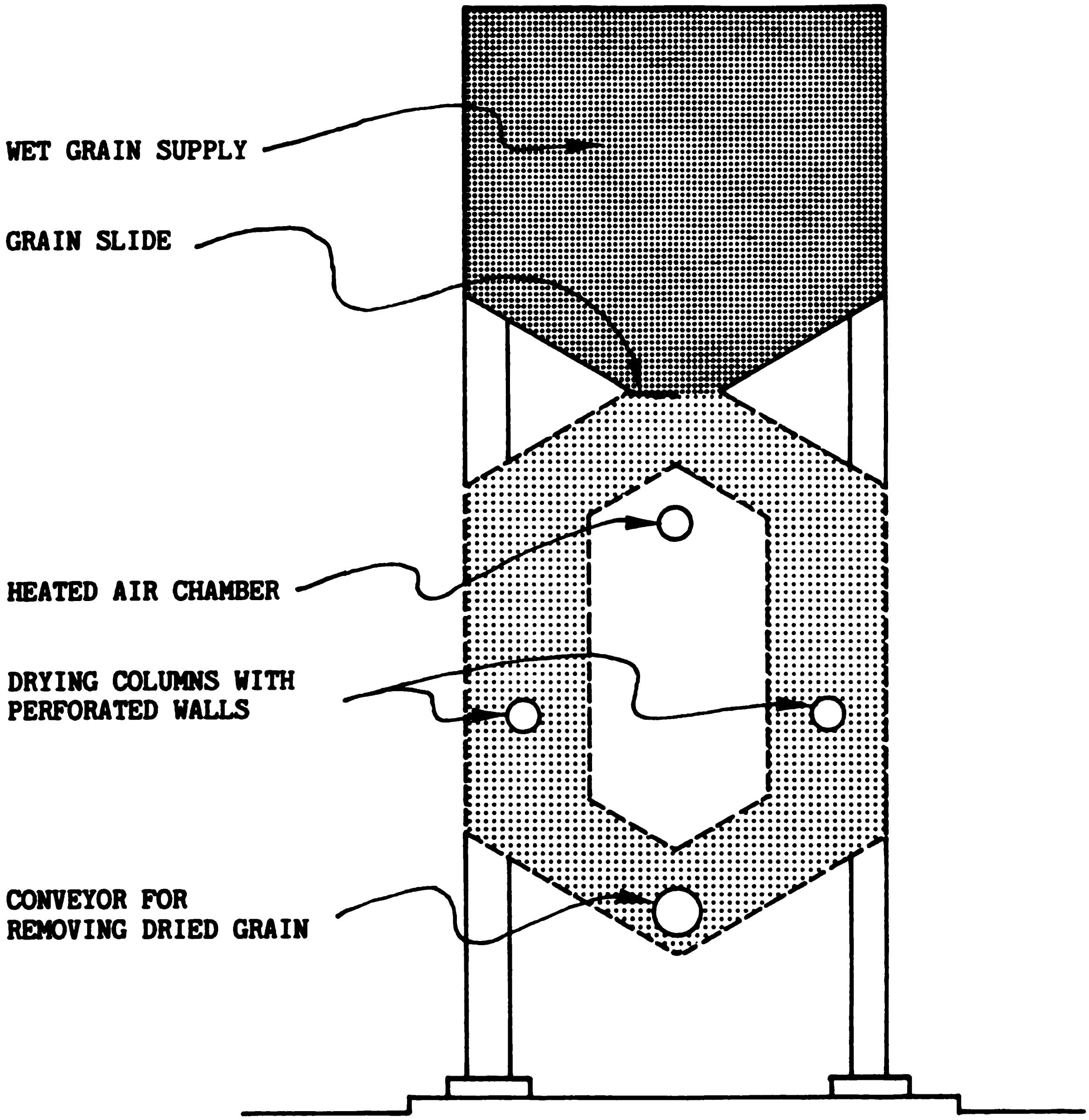

Figure 3.1.4 Cross-section of a column batch dryer (Brooker et al., 1974).

lower in efficiency than the natural and low temperature air drying, the drieration, and the continuous in-bin counterflow systems (Table 3.1.1).

3.2 CONTINUOUS FLOW DRYERS

In concurrentflow drying the grain moves in the direction of the air flow (Figure 3.1a). The CCF dryer will be discussed in detail later.

In crossflow drying the air moves perpendicular to the grain. Figure 3.1b illustrates that:

(1) the grain is driest and hottest at the air inlet side,

(2) the grain at the air inlet side approaches the drying air temperature, and

(3) the grain at the exhaust side is cooler and wetter than at the air inlet side.

The resulting temperature and moisture gradients cause a lowering of the grain quality.

In counterflow drying the grain moves countercurrently to the flow of air. Figure 3.1c shows that the driest grain reaches the highest temperatures. This limits the drying air temperature because of grain quality considerations (breakage susceptibility and heat damage). Therefore, counterflow systems can best be employed for cool-

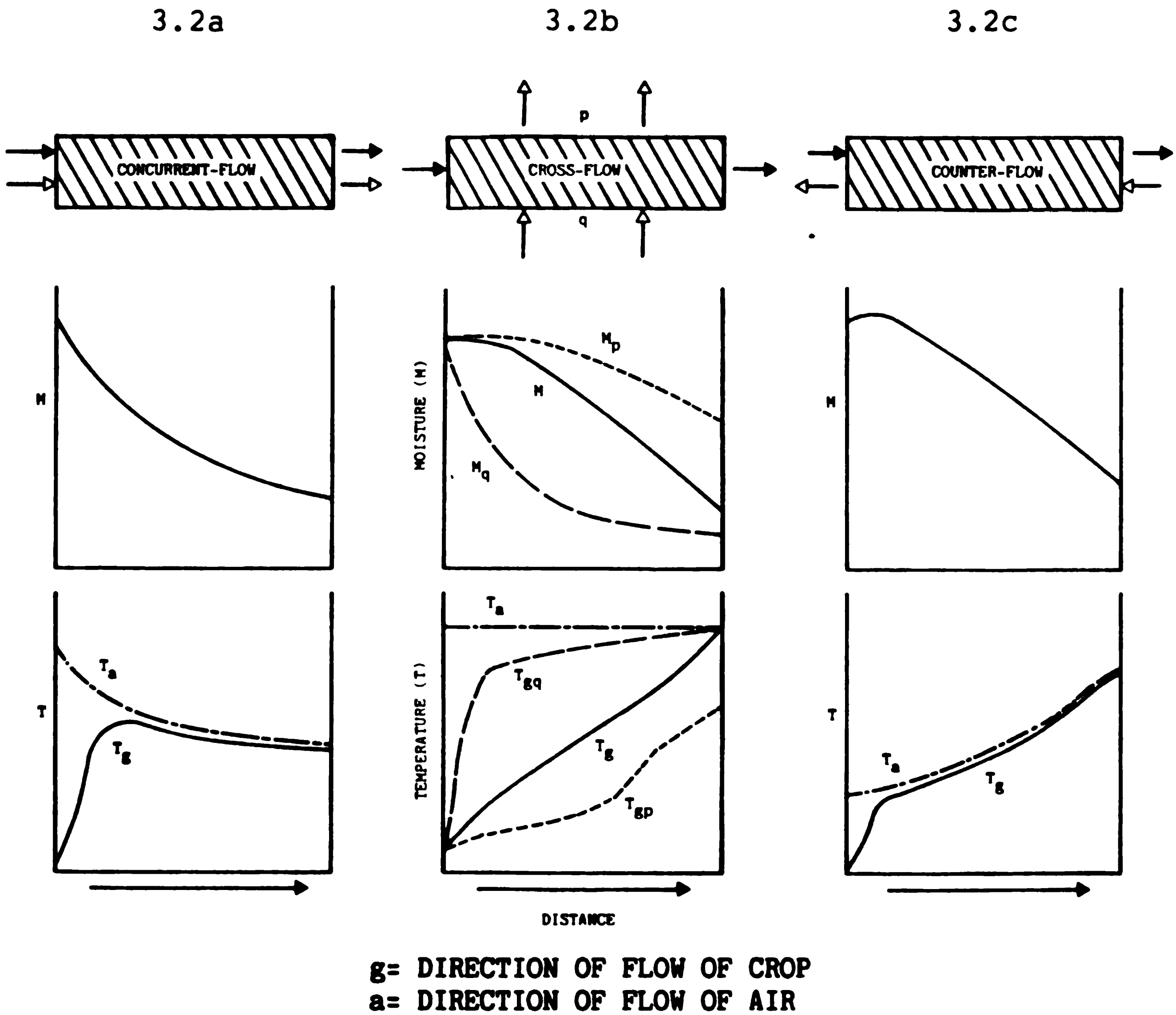

Figure 3.2a Moisture and temperature changes during concurrentflow drying (Nellist, 1982).
3.2b Moisture and temperature changes during crossflow drying (Nellist, 1982).
3.2c Moisture and temperature changes during counterflow drying (Nellist, 1982).

ing rather than for drying grain. A counterflow cooling system is used with the CCF dryer.

3.2.1 CROSSFLOW (CF) DRYERS

The crossflow dryer is the most commonly used continuous flow dryer in the U.S.A. Figure 3.2.1a is an example of a CF dryer. The grain flows from the wet-grain holding bin through the grain columns, and is discharged at the bottom. The upper portion of each column is used for drying, the lower part for cooling.

CF dryers are relatively inexpensive and have a moderate to high drying capacity. Operating temperatures can be as high as 121°C and the airflow rate varies from 75.3 to 129.2 m^3/min-ton (70 - 120 CFM/bu).

Conventional CF dryers are energy inefficient and have lowered grain quality. Bakker-Arkema (1984) reported that:

(1) conventional CF dryers may have a moisture content gradient as high as 20% across the column and a grain breakage susceptibility increase as high as 50%,

(2) conventional CF dryers may have energy efficiencies of 7000 KJ/Kg, and

(3) various design improvements such as air recirculation, reversal of airflow, grain inverters, differential grain-speed (DGS) devices, and tempering improve energy efficiency and help maintain the quality of grain.

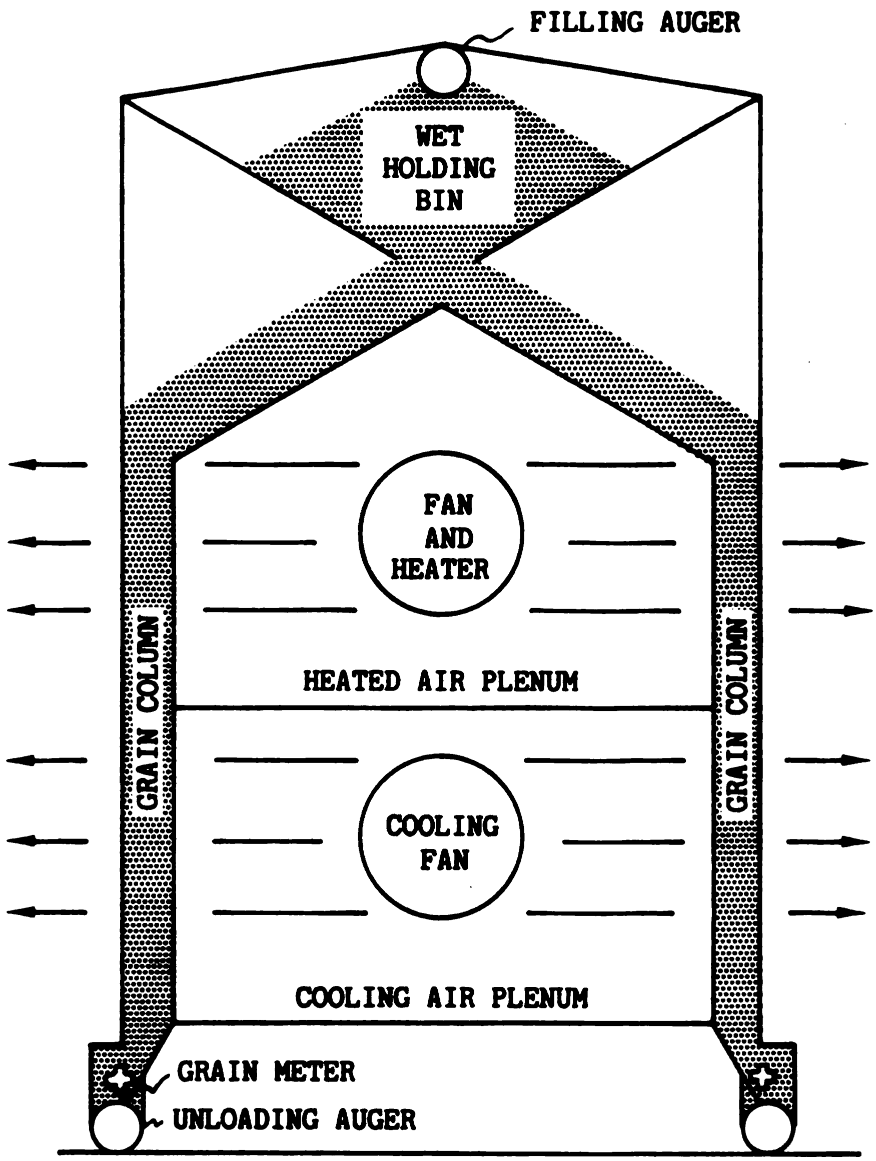

Figure 3.2.1a Crossflow dryer with forced-air drying and cooling (Brooker et al., 1974).

Bakker-Arkema and Schisler (1984b) described a commercial (Figure 3.2.1b) DGS-CF dryer that dries corn from 30% to 15% M.C. with only a 2.3% moisture gradient across the column. They also dried corn from 19% to 14% M.C. with less than a 1% moisture gradient across the column.

3.2.2 MIXED-FLOW (CASCADE) DRYERS

A continuous mixed-flow dryer dries grain by a combination of crossflow, concurrentflow, and counterflow actions. This takes place when the grain flows over rows of alternate inlet and exhaust air ducts. The cascade dryer is popular in Europe and South America but is not used in the U.S. probably because it requires pollution controls (Bakker-Arkema et al., 1983b). The initial cost is intermediate to high. The performance of the mixed-flow dryer is similar to the CCF dryer (Nellist, 1982). Bakker-Arkema (1984) reported energy efficiencies of 3500-4000 kJ/Kg for drying corn.

A= OUTER HOPPER
B= OUTER TAPERED GRAIN COLUMNS
C= PLENUM
D= TEMPERING HOPPER
E= INNER DRYING COLUMNS
F= COOLING ZONE
G= GRAIN EXIT

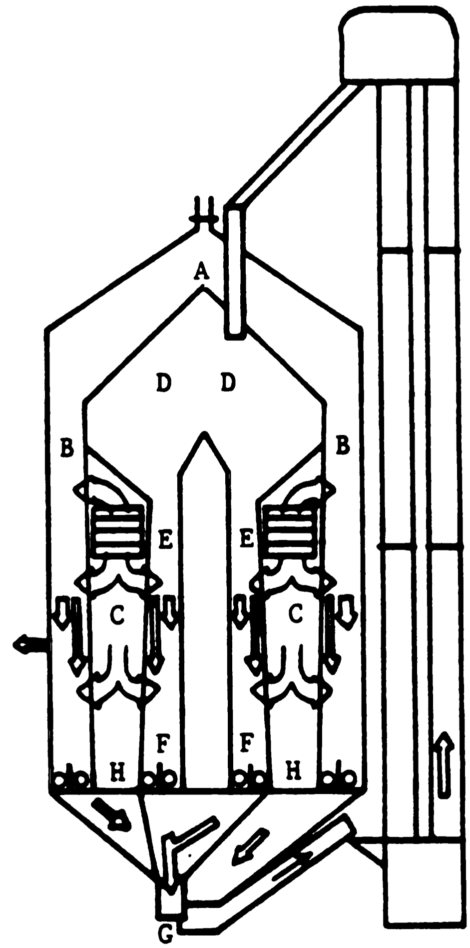

Figure 3.2.1b Differential Grain Speed crossflow dryer (Bakker-Arkema and Schisler, 1984b).

3.3 COMBINATION DRYING SYSTEMS

Combination drying is defined as a system in which high-temperature, high speed drying down to 18 to 22% M.C. is followed by in-bin low-temperature drying and cooling (Morey et al., 1978). The high temperature dryer may be batch or continuous flow and the low-temperature dryer may use in-bin natural or low-temperature drying air. The above systems are also referred to as partial high-temperature drying. The initial cost involves a high and low-temperature drying system.

Combination drying systems increase drying capacity up to 100% (Brook, 1979c), decrease energy consumption up to 50% (compared to batch dryers) (Kalchik et al., 1979), and help maintain the grain quality (Gustafson et al., 1978). Gustafson et al. (1978) reported that combination drying of corn with a final moisture content during the high-temperature phase at or above 18% significantly reduces the susceptibility to mechanical damage compared to conventional high-temperature drying.

Dryeration is a special case of combination drying (Bakker-Arkema, 1984). Dryeration is a process that involves high-temperature drying to 15 to 18% M.C., 6 - 8 hours of tempering in a bin, and then slow cooling with ambient air (1.0 m^3/min-ton). The final M.C. is 14 to 15.5%. Table 3.3 shows how much moisture can be lost with tempering and then cooling (McKenzie et al., 1966). For normal harvest moisture contents of 24 - 26%, dryeration saves 20% of the energy normally used in a crossflow dryer and dryeration increases the drying capacity by 25-40% for the high-temperature dryer (Brook, 1979e).

TABLE 3.3

CORN MOISTURE REDUCTION DURING COOLING AT 0.54 m^3/MIN/TON (1/2 CFM/BU.)

Hot Corn Temperature	Moisture reduction Average	(6 tests) Range
°C	Per cent	Per Cent
53.3	1.7	1.5--1.9
61.1	2.1	1.7--2.3
66.7	2.5	2.0--3.1

(McKenzie et al., 1966)

3.4 CONCURRENT/COUNTERFLOW (CC/CF) DRYERS

The concurrent/counterflow (CC/CF) dryer was developed from a Swedish patent by Oholm during the 1970's and appears to have the potential to become the major grain drying technique of the 1980's (Bakker-Arkema, 1984). This CC/CF dryer may consist of one, two or three drying stages with a counterflow cooling stage attached. Figure 3.4a shows a single stage CC/CF dryer. The wet grain enters the top via an auger, passes through a CCF drying bed and a counterflow cooling bed and is unloaded. Figure 3.4b shows a block diagram of a two stage CC/CF dryer. Tempering between the drying stages improves grain quality and energy efficiency. Recirculation increases the energy efficiency. Figure 3.4c is a schematic of the Blount CCF drying floor and shows the mixing of the drying air and the grain.

The CC/CF dryer has the most complex design of the continuous flow dryers. The CC/CF dryer has advantages over the mixed-flow and crossflow dryers because of its improved energy efficiency and high grain quality characteristics. In the CC/CF drying process (see Figures 3.2a - c):

(1) the grain and drying air flow in the same direction through a deep (0.61-0.91m) drying bed and a counterflow (1.22-1.83m) cooling bed,

(2) the grain exposure to the initial drying air temperature (DAT) is brief (30 seconds or less); the grain and DAT approach each other while in the middle of the drying bed,

(3) the wettest grain encounters the hottest air which results in rapid cooling of the drying air due to the high rate of evaporation,

(4) tempering (used in multistage units) allows for moisture and temperature gradients in the kernel to equalize,

(5) the coldest grain meets the coldest air in the counterflow cooling bed, and

(6) each kernel receives a similar drying, tempering and cooling treatment.

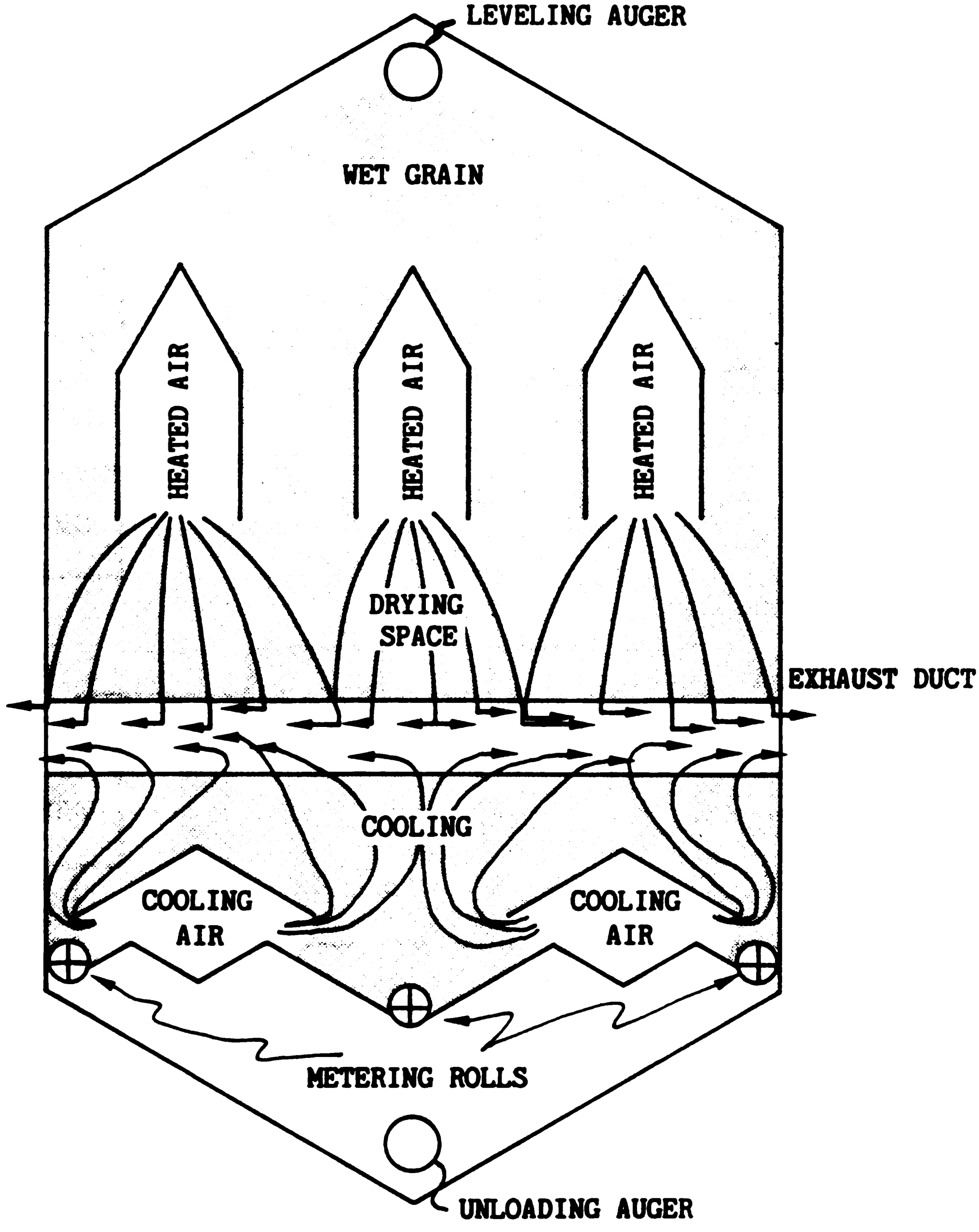

Figure 3.4a Schematic of an on-farm concurrentflow dryer (Brooker et al., 1974).

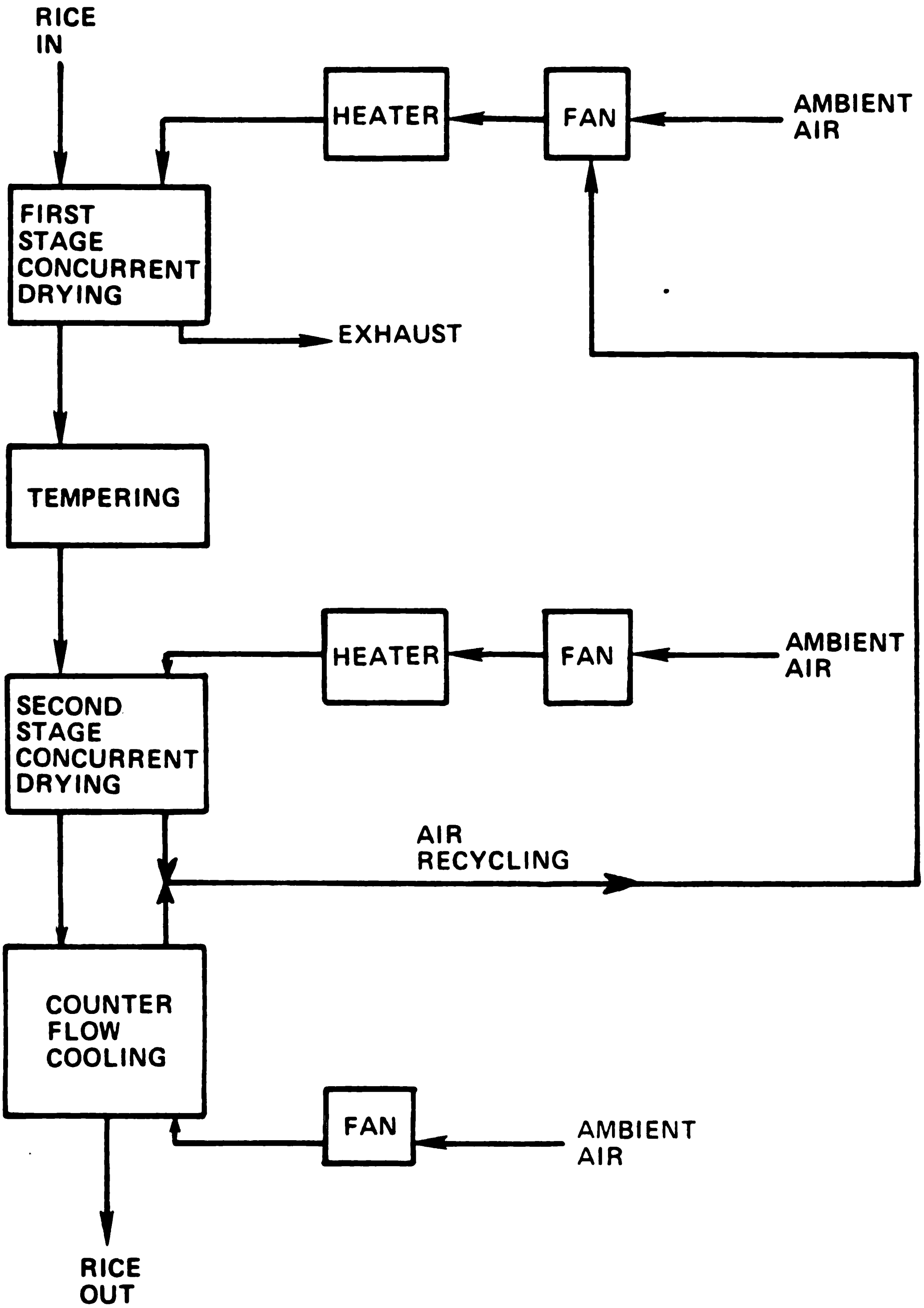

Figure 3.4b Block diagram of a two-stage CCF rice dryer with counterflow cooler and air recirculation (Fontana, 1983).

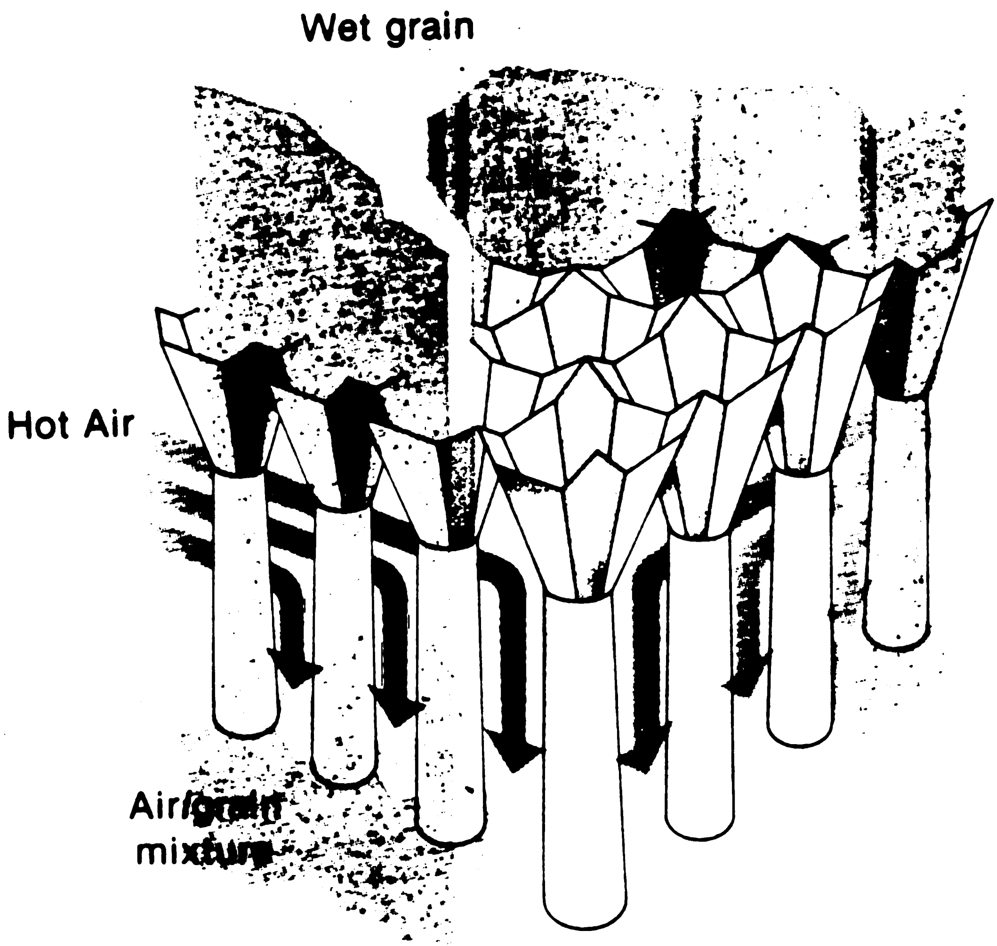

Figure 3.4c Schematic of the drying floor of the Blount concurrentflow dryer (Fontana, 1983).

In the CC/CF dryer the maximum DAT is a function of the type of grain, of the grainflow and of the initial M.C. of the grain. Thus, high inlet air temperatures are possible. This increases energy efficiency and reduces the airflow rate (Isaacs and Muhlbauer, 1975).

The deep drying-bed results in improved energy efficiencies (Brooker et al., 1974) and allows for tempering to take place which relieves stress cracking (Bakker-Arkema et al., 1972). Tempering between drying stages improves the energy efficiency, the grain quality and the drying rate (Bakker-Arkema et al., 1982).

The counterflow cooling system subjects the hot grain to a slow, gentle cooling because the temperature difference between the cooling air and the grain is usually not over 5°C to 10°C (Bakker-Arkema, 1984). The counterflow cooling process usually produces excellent grain quality (Bakker-Arkema and Schisler, 1984a).

The CC/CF dried grain is uniform in M.C. and temperature when leaving the dryer. This eliminates the need for mixing as is required in the CF dryers.

3.5 CCF DRYER LITERATURE REVIEW

With the increase of fossil fuel prices, fuel consumption reduction has become a concern for dryer manufacturers, farmers and grain elevator operators. The CC/CF dryer performance is a leader among continuous-flow systems with respect to energy efficiency. The energy efficiency of the CC/CF dryer is from 3000 to 3800 KJ/kg while the comparable mixed-flow and crossflow dryers are 3500-4000 KJ/kg and 3700-7000 KJ/kg respectively (Bakker-Arkema, 1984).

Sokhansanj and Bakker-Arkema (1981) determined that direct air recirculation and indirect air recirculation (heat pipes) produce up to 18% in energy savings. Bakker-Arkema et al. (1982) reported that the CC/CF dryer energy consumption while drying rice is half that of conventional rice dryers. Brook (1979e) found that the multistage CCF dryers are preferable to a single stage CCF dryer because of improved energy efficiency, temperature control, drying capacity and grain quality. The capital cost of adding another stage represents about 59.6% of the total cost of a single stage dryer and the cost decreased to 45.5% for a three stage dryer. Brook (1979e) also reported that the single stage CC/CF dryer is usually more energy efficient then most on-farm systems except for natural air drying (See Tables 3.5a and 3.5b).

TABLE 3.5a

DRYING SYSTEMS USED TO EVALUATE
COMBINATION DRYING TECHNIQUES

	TEMPERATURE	AIRFLOW
Deep Bin Drying	+0 C, +3 C	28%-5 m^3/min-tonne
		26%-3 m^3/min-tonne
		24%-2 m^3/min-tonne
		22%-1 m^3/min-tonne
Batch-in-Bin Drying	60 C	20 m^3/min-tonne
Crossflow	100 C	80 m^3/min-tonne
Concurrent	150 C	50 m^3/min-tonne
Dryeration		
-to 17% with Crossflow	100 C	80 m^3/min-tonne
-17 to 15% with Deep Bin	+0 C	1/2 m^3/min-tonne
Partial Heat Drying		
-to 20% with Crossflow	100 C	80 m^3/min-tonne
-20 to 15% with Deep Bin	+0 C	1 m^3/min-tonne

(Brook, 1979e)

TABLE 3.5b

ENERGY COST ($/tonne) FOR SEVERAL
SYSTEMS FOR DRYING GRAIN TO 15% WB.

Drying from	Deep Bin +0C	Deep Bin +3C	Batch-in Bin	Cross-flow	Con-Current	Dryer-ation	Partial Heat
30% wb	--	--	4.50	5.08	4.04	4.53	4.43
28	2.35	4.93	3.75	4.26	3.42	3.73	3.62
26	1.94	4.04	3.09	3.58	2.81	2.97	2.87
24	1.53	3.23	2.50	2.81	2.25	2.25	2.14
22	1.17	2.42	1.87	2.13	1.71	1.57	1.46
20	0.82	1.70	1.32	1.50	1.20	0.92	--

(Brook, 1979e)

The quality of CCF dried agricultural crops is reported to be excellent. Among the crops successfully dried are corn (Rodriguez, 1982), soybeans (Kalchik, 1977), pea beans (Brook, 1977), soft wheat (Ahmadnia, 1977), rice (Fontana, 1983) and sorghum (Bakker-Arkema et al., 1983a).

Hall and Anderson (1980) used (a single stage CCF dryer) DATs as high as 500°C without affecting corn product quality. Thompson et al. (1969) reported that DATs of less than 121°C results in acceptable wet millability of corn in a single stage CCF dryer. Walker and Bakker-Arkema (1981) reported that rice was dried successfully at 120°C without affecting the rice head yield. Bakker-Arkema et al. (1982) reported that multistage CCF rice dryers with built-in tempering can remove at least six points of moisture at DATs between 121°C and 177°C. Fontana et al. (1982) reported that inlet air temperatures of 140°C (top stage) and 80°C (bottom stage) for a two stage CCF dryer did not affect the rice seed viability; the fuel efficiency during these tests was 3500 KJ/kg.

CHAPTER 4

GRAIN QUALITY

This thesis is primarily concerned with the wet milling characteristics of artificially dried sorghum. The literature is sparse on this subject because commercial wet milling in the U.S. was discontinued in 1973. Today almost all sorghum in the U.S. is used for animal feed because corn is considered to have superior wet milling properties. Corn and sorghum are similar in composition, kernel structure, starch properties and ease of starch isolation (Watson and Hirata, 1954). Also, corn and sorghum wet milled products are used for the same purposes. Therefore, the wet milling characteristics of artificially dried corn will be considered when appropriate.

4.1 DESIRABLE WET MILLING CHARACTERISTICS FOR GRAIN SORGHUM

Desirable grain quality properties are (Brooker et al., 1974):

(1) appropriately low and uniform moisture content;

(2) low percentage of stress-cracked, broken and damaged

kernels and of foreign substances;

(3) low susceptibility to breakage;

(4) high test weight;

(5) high starch yield (millability) and quality;

(6) high oil recovery and quality;

(7) high protein quality;

(8) high viability;

(9) low mold count; and

(10) high nutritive value.

The importance of the above qualities varies with the use of the grain. The wet milling is primarily concerned with (5), (6) and (7) although the USDA standards for grain sorghum do not evaluate these properties. Selective buying of grain sorghum on the basis of (5), (6) and (7) is usually impractical because of the high volumes of grain wet milled daily. Therefore, the wet miller buys most of his grain at the market value determined by the USDA grain standards.

High quality wet milled sorghum kernels are clean, plump and whole, have a high test weight (Watson, 1970) and minimal damage due to insects, molds, artificial drying, and handling. Watson et al. (1961) reported that laboratory steeping and milling studies best indicate actual milling performance. However, these studies are too lengthy and involved for rapid quality determinations.

Freeman (1973) reported the following about the corn wet milling industry: (1) Available methods for evaluating grain on the basis of some important quality factors not considered in the official grade are often too complex and lengthy for routine use in a plant laboratory under any circumstance. [This is because most wet milling plants process 640,000 - 2,500,000 Kg of corn daily.]; (2) The suitability of corn for wet milling is related to the official grade and class designation in the following manner:

(a) Color: Only yellow corn is used.

(b) Test Weight: Low test weight is detrimental to the value of corn because it lessens storage silo and steeping tank capacity. Test weight of corn is determined by a combination of true density and its packing characteristics.

(c) Moisture Content: M.C. affects the kernel density and the packing properties. Grain with a high M.C. is more likely to mold and to give problems during unloading and cleaning.

(d) Broken Corn and Foreign Material (BCFM): An excessive amount of broken corn indicates inferior quality and increases cleaning requirements and loss of dry matter. Foreign material may include rodent hairs and feces, and various types of weed seeds unsuitable for food use.

Broken kernels too large to be removed in the normal cleaning operation may release starch granules during steeping. The free starch remains in the steepwater and causes fouling of evaporator surfaces during steepwater concentration. Excessive BCFM may indicate an unequal M.C. distribution and thus provide potential for mold growth.

(e) Damaged Kernels: Molding of kernels is the most common form of damage. Molded kernels result in decreased oil yield and quality (undesirable free fatty acids).

(f) Odor and Miscellaneous: Objectionable foreign odor caused by heating and molding indicates poor grain quality. Excessive amounts of stones represent dry matter loss.

(3) Factors not considered in official grade and class designation which can effect the value of corn for wet milling are:

(a) Oil Content and Distribution: 80 to 90% of the oil in corn is in the germ. Field shelling and handling can effect the oil recovery by chipping, cracking, and bruising the germ which can result in oil migrating to the endosperm.

(b) Oil Quality: The price of oil is 3 to 4 times that of starch. Molding can produce free fatty acids which require additional processing.

(c) Carotenoid Pigments: These pigments give the desirable yellow color to the shanks and skins of broilers and to the yolks of eggs.

(d) Starch Content and Quality: Uniformily low starch content is, in general, preferable to a high starch content because the economic value of protein and oil is higher. Starch that is high in protein content and low in viscosity is considered to be of low quality. High temperature drying of corn can decrease yield and quality of corn starch.

(e) Protein Content and Quality: The protein content is not affected by normal harvesting, and storage procedures. However, the quality may be impaired during drying.

(f) Mycotoxins: Mycotoxins are not a problem in wet milling because the wet milling process usually removes these toxic substances from the food products.

(g) Kernel Size, Shape and Uniformity: These qualities are of minor importance to the wet miller although small kernels have less oil content.

(h) Kernel Density: The true density of a grain sample is a good index of quality.

(i) Grain Preservatives: Grain preservatives are discouraged by the wet milling industry.

(j) Pesticide Residues: These are not a problem for wet millers.

(k) Viability: Corn of high viability is almost always excellent for wet milling.

(l) Stress Cracks: Corn with stress cracks is fragile and tends to break during handling. Breakage which occurs after the corn is purchased is lost to cleanings and reduces the product yields proportionately.

(m) Millability: The best measure of quality of corn for wet milling is provided by the results obtained by milling.

Clearly, the USDA Grain Standards are not always reliable to the wet miller in selecting quality grain.

4.2 QUALITY OF ARTIFICIALLY DRIED GRAIN

Heated air drying is often more popular than natural air drying of grain because it is quick, simpler to manage and capable of producing a more uniform product. Some of the potential disadvantages in heated air drying are: (1) increased energy costs, (2) loss of grain quality due to heat damage, and (3) increased initial cost of the dryer. Nellist (1980) reported that dryer design is very important in determining the quality of the grain.

Germination (viability) is the most sensitive indicator of grain damage. Factors that effect the loss of viability during a particular drying treatment are:

(1) the initial viability;

(2) the temperature of the grain;

(3) the M.C. of the grain; and

(4) the time of exposure.

Nellist (1981) reported that:

(1) the poorer the seed, the more severe the damage by a given drying treatment;

(2) at constant temperature and M.C., seed death is normally distributed with time; and

(3) with sound management, drying at near ambient temperature in bulk stores can be a safe way to preserve seed viability.

Nellist (1982) reported that:

(1) germination is an excellent means of reflecting chemical and physiological changes;

(2) each batch of seeds has its own initial germination and apparent resistance to heat damage; and

(3) the germination test has an experimental error of 1 to 2% which limits its sensitivity in determining heat damage.

Ghaly et al. (1974) reported that wheat damaged during artificial drying has a decrease in both viability and loaf size.

Gustafson and Morey (1981) found that the drying air temperature within the grain mass is a consistent indicator of potential germination but not of breakage susceptibility within a crossflow grain dryer column.

Watson and Hirata (1962) reported the following about a column batch dryer (except for the airflow rate which used a CF dryer) with drying times normally greater than one hour:

(1) corn dried to preserve viability should be suitable for wet milling;

(2) the grain temperature which causes a significant drop in viability is a function of initial M.C. of the grain, the temperature and relative humidity of the drying air and the drying airflow rate;

(3) corn dried at 82.2°C or higher shows evidence of reduced millability;

(4) initial M.C. (up to 32%) of corn and airflow rate (up to 194.8m^3/min/ton (181 CFM/bushel) have no effect on milling results;

(5) high relative humidity in a batch dryer increases the degree of damage sustained by the corn dried at 82.2°C; and

(6) viability of the grain is reduced or destroyed by drying conditions less severe than those which adversely affect millability.

MacMasters et al. (1959) reported that the germination of corn is drastically decreased at drying air temperatures above 60°C while the millability remains acceptable at drying air temperatures as high as 71.1°C (1-2% loss) (the drying conditions caused the grain temperature to reach the drying air temperature). The drying times ranged from 1.0 - 9.0 hours (See Table 4.2). These are extremely long exposures at high drying air temperatures. At 71.1°C, the drying time was 2.0 to 4.0 hours with only a slight drop in millability; also viability ranged from zero up to 29%. The grain was probably at 71.1°C for more than an hour!

TABLE 4.2

MEAN PERCENTAGE OF STARCH RECOVERY AND MEAN PERCENTAGE OF PROTEIN IN STARCH ASSOCIATED WITH DRYING TEMPERATURES

DRYING TEMPERATURE °C	STARCH RECOVERY %	VIABILITY RANGE %	PROTEIN IN STARCH %	APPROX. DRYING TIME AVE. HR. HR
Control	83.10	95-99	0.836	
48.9	82.45	28-99	0.836	6.0-9.0
54.6	82.44	26-98	0.741	3.0-7.0
60.0	80.41	0-9~~0~~4	0.807	2.0-4.0
65.6	81.71	0-89	0.837	2.0-5.0
71.1	80.87	0-29	0.801	2.0-4.0
82.2	79.46	0	0.958	1.0-2.5
93.3	74.03	0	1.032	1.0-1.5

Corn with 30% and 20% M.C. lumped together.
(MacMasters et al., 1959)

4.3 FACTORS EFFECTING GRAIN QUALITY DURING ARTIFICIAL DRYING FOR WET MILLING

Factors which can effect grain quality during artificial drying include:

(1) the drying air temperature,

(2) the design of the dryer (method used),

(3) the grain temperature history in the dryer,

(4) the inlet air humidity,

(5) the previous grain history

(6) the initial and final M.C.,

(7) the variety and species of grain,

(8) the time of grain exposure to the maximum temperature,

(9) the rate of drying,

(10) the handling of the grain, and

(11) the source of fuel used to heat the air.

These factors are all interrelated. The grain temperature history in the dryer has the most profound effect. Grain temperature history is mostly a function of the dryer design.

A decrease in the millability of slowly dried corn has been attributed to the species and variety of the grain, to the soil and weather conditions (MacMasters et al., 1959), to the field harvesting procedure (Vojnovich et al., 1975), and to the maturity of the grain (Thornton et al., 1969). Hutt et al. (1978) found that contamination of grain has a negligible effect on millability when direct heating with gaseous fuels is practiced. Hurburgh and Moechnig (1984) reported that dry matter losses while drying corn can average 0.88% of the initial weight with a CF dryer.

Thompson and Foster (1963) reported that the drying rate of shelled corn is directly related to the number of stress cracks developed, and that rapid cooling causes an increase in the number of stress cracks. Vojnovich et al. (1975) reported that rapid drying (.25-0.5 hrs) of corn at 148.9°C with a very high airflow rate [484m^3/min ton (450 CFM/bushel)] is very detrimental to starch yield and quality and also to oil yield.

Freeman (1973) reported that except for the inherent grain characteristics, the method of drying probably has the greatest effect on millability of corn. He also reported that drying corn with a high DAT heat from 30% to 15% M.C. in a single pass resulted: (1) in a 25% reduction in production capacity, (2) in poor dewatering of course fiber, (3) in an increase of starch in the gluten with a correspondingly lower starch yield, (4) in a higher protein content of isolated starch, and (5) in a low starch viscosity. McGuire and Earle (1958) found that a decrease in soluble protein in the steepwater with increased drying temperatures suggests that heat-denaturation of corn endosperm protein occurs. Freeman (1973) reported that high temperature drying decreases the test weight, that kernel protein is found to "case harden" and resists kernel shrinkage during drying. The millability of corn has been shown to decrease as the initial M.C. (especially over 25%) increases at high drying temperatures (Watson and Hirata, 1962 and Brown et al., 1981).

4.3.1 SAFE DRYING AIR TEMPERATURES

Conventional drying systems have caused existing safe drying air temperature regulations or recommendations to assume that the temperature of some grain kernels approaches or reaches the drying air temperature almost immediately after drying begins. However, grain takes time to warm up and wet grain may be cooled by evaporation. For example, a period of 60 to 90 seconds is necessary for corn to reach equilibrium temperature with water, when the water temperature is kept constant (Sokhansanj, 1974). The specific heat of sorghum at 20% M.C. (w.b.) is 1.647 KJ/kg°C whereas the latent heat of evaporation is 2483KJ/Kg. When evaporation takes place, large amounts of energy are released from the kernel causing a cooling effect.

Nellist (1981) found that the treatment determines the damage to viability of barley. He used the following methods on barley at 68°C: (1) heating in a water bath, (2) drying in a static thin layer, and (3) drying a grain stream moving concurrently with an air stream. The viabilities were 0%, 74.2% and 96.7%, respectively, because the grain temperature histories varied with the method used. He concluded that existing safe drying air temperature recommendations can discourage the development of energy efficient grain dryers such as the CCF dryer.

Grain temperature history determines grain quality, not necessarily the drying air temperature. Sokhansanj (1974) showed that time, temperature and initial moisture content are factors affecting germination of corn when it is immersed in a constant-temperature water bath (60 - 90 seconds). He arrived at the following conclusions; (1) Temperatures in the 60°C range do not affect germination of corn at lower moisture contents (16%); in fact, these temperatures may improve germination compared to the control samples; this may be due to activating certain enzymes which are responsible for breaking the dormancy of the embryo; temperatures above 60°C reduce germination and at 82.2°C no germination is detected for moisture contents above 16% (w.b.); (2) Starch, protein and mineral losses are negligible with temperatures as high as 82.2°C; (3) Length of heating time affects the viability of the corn, but it is not as strong as temperature effect; (4) As the initial moisture content of the corn increases, the viability will decrease; and (5) More stress cracks and damage are observed at 82.2°C than at 60°C for corn.

4.3.1.1 DRYER DESIGN (METHOD)

The most important difference in a grain dryer is the relative direction of flow of the grain and the air. There are three general flow schemes: (1) concurrentflow, (2) counterflow, and (3) crossflow (see section 3.2).

Nellist (1982) concluded that a mixed-flow or crossflow dryer maintains the viability of wheat at a DAT of 66°C. Fontana et al. (1982) reported that drying inlet air temperatures of 140°C and 80°C for long grain rice (maximum rice temperature, 60°C) in a commercial two-stage CCF dryer do not reduce the viability or head yield. They also reported that a comparable CF dryer operates at 90°C and 50°C.

The time of grain exposure to the initial drying air temperature has a significant effect on the grain temperature history. CCF dryers use the grainflow rate to limit the grain exposure to high inlet air temperatures. A CCF dryer operating at a drying air temperature of 266°C was shown to only produce a maximum grain temperature of 93.3°C for 100 seconds. However, a comparable CF dryer operating at 93.3°C was shown to reach an inlet air side grain temperature of 90.6°C quickly and to remain there for the duration of the drying section (Bakker-Arkema et al., 1977).

A single and a two-stage CCF dryer are able to dry soybeans at temperatures as high as 232.2°C without the loss of oil yield (Kalchik, 1977); the maximum soybean temperature was 82°C.

Watson and Hirata (1962) concluded that a crossflow dryer operating at a drying air temperature of 65.6°C causes no loss to viability of corn at a low airflow rate (63.5m^3/min ton (59 CFM/bu)). However, a successive drop of 10% in the viability occurs at medium [131.3 m^3/min ton (122 CFM/bu)] and high [148.5 - 194.7m^3/ton (138 - 181 CFM/bu)] airflow rates.

LeBras (1982) found that the caloric-flow rate (KJ/s) is responsible for reduction in millability of corn not the airflow rate. He also concluded that staging and combination drying improve millability compared to one-stage drying.

The cooling method of a grain dryer can maintain or decrease grain quality. When grain is cooled too rapidly after drying, an increase in breakage susceptibility can occur (Gustafson and Morey, 1981). Delayed cooling such as in the dryeration process (Gustafson et al., 1979) or slow cooling as in the CC/CF dryer (Bakker-Arkema and

Schisler, 1984a), minimizes the breakage susceptibility increase.

Grain dryer design clearly determines the operating air temperature and has an important effect on grain quality.

4.3.1.2 RECOMMENDED SAFE DRYING AIR TEMPERATURES FOR WET MILLING OF CORN

Safe drying air temperatures (DATs) in the literature vary for corn wet millability from 60°C up to 120°C. The method of drying reflects the recommended DAT.

Watson and Hirata (1962) found that DATs of 82.2°C and above usually show evidence of reduced millability with a batch dryer and a significant decrease in millability (3-5%) occurs in a continuous crossflow dryer at a DAT of 87.8°C. MacMasters et al. (1959) used a column batch dryer with drying times always one hour or more for corn. They reported that on the basis of recovery and quality of the starch a DAT of 71.1°C gives acceptable millability.

Watson and Sanders (1961) reported that damage from artificial drying in a small farm batch dryer is detectable by cutting thin sections (10 micrometers) of horny endosperm from water-softened corn kernels followed by steeping. They determined the extent of steeping by measuring the increase in light transmission through the section as starch was released. They observed the following when drying corn from 32% M.C. to 12% w.b.: (1) a DAT of 48.9°C gives normal starch release, (2) at 93.3°C the starch is irreversibly damaged and only one-third of the normal amount is released, and (3) at 82.2°C the starch release is only two-thirds of normal when steeping takes place at 52°C; however at 60°C a normal release occurs.

Brown et al. (1981) reported that a DAT of 60°C is safe for corn wet milling. This was concluded after drying corn in thin layers at various initial M.C.s (15-20%, 20-25%, and 25-30% (w.b.) with a DAT of 80°C or 100°C. A thin layer (4 cm) was dried in a forced air convection oven.

LeBras (1982) reported that acceptable starch yield and quality are obtained at a DAT of 80°C in a batch dryer with an airflow of 1600 $m^3/h\text{-}m^3$ (33.3 CFM/bu). The latest European commercial wet milling technology was used. Thompson et al. (1969) received acceptable millability for CCF dried corn at 121°C. Clearly, most safe DATs which are recommended assume that the corn temperature reaches the DAT.

4.3.1.3 SAFE DRYING AIR TEMPERATURES FOR WET MILLING OF SORGHUM (A COLUMN BATCH DRYER)

The sorghum drying literature is sparse because sorghum is a feed grain in the U.S. and corn is considered of higher economic value. Iowa (1957) recommended natural air drying only when the M.C. is 20% or less (w.b.). Sorensen et al. (1957) reported that: (1) on-farm bin drying with natural air is the most practical method to preserve grain quality, (2) bin depths should be 2.44m or less, and (3) natural air dried sorghum should reach 15% M.C. in 8 days to prevent molding.

Sorensen and Person (1970) reviewed different on-farm drying methods of sorghum. They reported the following:

(1) The three major methods of drying sorghum with forced air are: (a) natural-air drying, (b) drying with supplemental heat (5.6°C to 8.3°C) and (c) heated air drying (batch and crossflow dryers).

(2) Natural-air drying: The advantages are a low initial investment, a reduced fire hazard and a more uniformly dried product. The disadvantages are the long time required in drying, and the danger of spoilage.

(3) Drying with supplemental heat: The chief advantage is that drying can be accomplished regardless of weather conditions and a shorter drying time is needed. The disadvantages are overdrying the grain, higher initial equipment costs and a danger of fire.

(4) Heated-Air Drying: The chief advantages of heated-air drying are (a) the comparatively short drying period, (b) drying can be accomplished regardless of weather conditions, and (c) the high drying capacity. The main disadvantages are (a) the higher initial equipment costs,

(b) the fire hazard, and (c) the over-drying of grain reducing grain quality.

(5) Batch-In-Bin Dryer: The grain depth is usually 0.61m or less. The recommended maximum air temperatures for drying feed and seed sorghum are 54.5°C and 43.3°C respectively with a minimum airflow rate of 32.3m^3/min/ton (30 CFM/bu).

(6) Column-Type Batch Dryer: The DATs range from 54.4 to 93.3°C depending on the rate of airflow [32.3 to 129.2m^3/min/ton (30 - 120 CFM/bu)].

(7) Crossflow Dryers: DATs vary from 65.6°C to 93.3°C with airflow rates of 107.6 - 215.3m^3/min/ton (100 - 200 CFM/bu).

(8) Planting seed DATs should be 43.3°C (110°F) or less.

McNeal and York (1964) recommended that DATs should be 54.4°C or less in a commercial column-batch dryer to insure viability and the harvest M.C. should be as low as possible (less than 22%).

Sorensen et al. (1949) and Zipf et al. (1950) concluded the most extensive study on the artificial drying of sorghum and its effect on the wet milling characteristics. A farm column-batch dryer with two columns of 1.82m high, 2.74m long, and 0.254m wide was used in both studies. Only one column was operated during the experiment with a holding capacity of 1,363.6 Kg (3000 pounds) of sorghum.

Natural gas was the heat source. All samples were cleaned before drying and after drying representative samples were milled in duplicate (See Tables 4.3.1.3a, b, and c for results).

The variety Martin was dried at three different initial M.C. levels [high (21-26%), medium (17-20%) and low (14-16%)], and Early Hegari at two levels (medium and low). Samples were either dried to 11-13% M.C. or 7-9% M.C.

The drying air temperatures (DATs) were 51.7°, 65.6°, 79.4°, 93.3° and 110°C. All samples except, 37 and 50, were graded as NO. 1. This means that the breakage was less than 2% and the test weight was at least 57.0 pounds/bushel. The variety Early Hegari was found to dry more rapidly than Martin, to have acceptable germination at a DAT of 79.4°C with low initial M.C., and to have acceptable wet millability in all cases.

Martin had an acceptable germination at an M.C. of 20% at a DAT of 79.4°C. All samples of Martin had acceptable wet milling characteristics except low and medium M.C. samples dried to 7-9%. These samples had inferior starch yield (2-6% losses) with a (0 to 0.36%) protein increase in the starch. The apparent damage to Martin correlated strongly with the M.C. of the grain and the extent of drying but not with the temperature. Batch No. 50 which was dried at 110°C for 2.58 hours wet milled well; the starch yield and quality were acceptable.

The fuel efficiency:

(1) ranged from 3700 to 9430 KJ/Kg for drying Early Hegari and Martin;

(2) improved with increasing the DAT; and

(3) significantly decreased with samples dried to 7 - 9% M.C. (See Table 4.3.1.3d).

Sorensen et al. (1949) concluded that the best wet milling sorghum has an initial low (17 - 20%) M.C., is dried to 11 - 13% M.C., and can be dried at DATs up to 110°C in a column batch dryer.

TABLE 4.3.1.3a

ARTIFICIALLY DRIED WET MILLED SORGHUM RESULTS

	VARIETY: EARLY HEGARI[1]								MARTIN[4]				
BATCH NO.	5	6	7	8	9	10	11	12	18	20	50	51	52
Initial M.C. Range %	17-20	17-20	17-20	17-20	14-16	14-16	14-16	14-16	17-20	17-20	21-26	17-20	17-20
Final M.C. Range %	11-13	11-13	11-13	11-13	11-13	11-13	11-13	11-13	7-9	7-9	7-9	11-13	11-13
M^3/min ton	161.8	134.5	132.5	126.4	155.7	144.5	120.3	122.4	153.7	137.5	46.5	140.6 110.2	122.4 134.5
Drying Air Temp, ^{o}C	51.7	65.7	79.4	96.1	51.7	65.7	82.2	93.3	65.7	93.3	110	65.7 110	110 65.7
Drying Time Hours	2.92	1.67	1.04	0.83	1.30	1.07	0.73	0.50	2.58	1.27	2.57	1.02	1.00
Max Grain Temp At Ctr of 10 inch Column ^{o}C	46.1	56.7	63.3	68.9	46.1	56.7	65	70.6	58.3	79.4		82.8	76.1
Germination % Air Dried					80	84	73	83	74	81		80	80
Germination % Arificially Dried	76	66	61	50	82	82	77	74	73	27		72	43
Starch Yield %	83.7	84.3	83.4	81.4	83.6	84.4	83.2	84.2	84.6	85.0	82.0	84.2	84.4
Protein in Starch, %	0.39	0.36	0.38	0.39	0.36	0.43	0.41	0.42	0.39	0.40	0.31	0.34	0.33
Protein in Gluten	38.1	36.6	36.9	35.0	37.2	28.1	36.9	37.7	36.6	37.4	36.8	41.2	38.3

1) All early hegari samples were no. 1 white kafir after drying.
2) 30 minutes at 65.7°C and 30 minutes at 110°C.
3) 30 minutes at 110°C and 30 minutes at 65.7°C.
4) # 51 and # 52 were no. 1 yellow mild after drying, # 50 was sample grade yellow milo ("toasted" odor) otherwise no. 1.

Sorensen et al. (1949)

TABLE 4.3.1.3b

ARTIFICIALLY DRIED WET MILLED SORGHUM RESULTS

VARIETY: MARTIN*

BATCH NO.	25	26	27	28	29	30	31	32	33	34	35	36
Initial M.C. Range %	21-26	21-26	21-26	21-26	17-20	17-20	17-20	17-20	14-16	14-16	14-16	14-16
Final M.C. Range %	11-13	11-13	11-13	11-13	11-13	11-13	11-13	11-13	11-13	11-13	11-13	11-13
m^3/min ton		162.8			154.7	120.3			137.5	126.4	111.2	106.2
Drying Air Temp, ^oC	51.7	65.6	79.4	96.3	57.7	65.6	79.4	93.3	51.7	65.6	82.2	93.3
Drying Time Hours	7.00	3.45	2.65	2.08	3.42	1.32	1.08	1.23	1.33	0.88	0.70	0.52
Max Grain Temp At Ctr of 10 inch Column ^oC					54.4	63.9			46.1	55.6	61.7	68.3
Germination % Air Dried									93	93	93	93
Germination % Arificially Dried					88	82			90	94	89	75
Starch Yield %	80.5	82.6	85.7	88.0	82.0	85.0	82.5	82.9	83.0	82.2	83.7	84.1
Protein in Starch, %	0.32	0.38	0.36	0.36	0.36	0.34	0.33	0.34	0.33	0.33	0.32	0.33
Protein in Gluten	45.3	44.6	40.6	41.4	43.5	39.5	38.9	37.8	38.0	36.3	37.2	39.2

1) All samples were no. 1 yellow mild after drying (#25 and #25 had a slight "toasted odor").

Sorensen et al. (1949)

TABLE 4.3.1.3c

ARTIFICIALLY DRIED WET MILLED SORGHUM RESULTS

VARIETY: MARTIN*

BATCH NO.	37	38	39	40	41	42	43	44	45	46	47	48
Initial M.C. Range %	21-26	21-26	21-26	21-26	17-20	17-20	17-20	17-20	14-16	14-16	14-16	14-16
Final M.C. Range %	7-9	7-9	7-9	7-9	7-9	7-9	7-9	7-9	7-9	7-9	7-9	7-9
M^3/min ton	149.7	104.2			141.6	134.5	117.3	117.3	128.4	119.3	111.2	97.1
Drying Air Temp, ^oC	51.7	65.6	79.4	96.3	57.7	65.6	79.4	93.3	51.7	65.6	79.4	93.3
Drying Time Hours	8.50	4.72	3.87	3.08	7.00	3.58	2.33	1.90	5.75	2.50	1.53	1.17
Max Grain Temp At Ctr of 10 inch Column ^oC	47.2	57.2			47.8	57.8	68.3		47.2	57.2	69.4	77.2
Germination % Air Dried									95	95	95	95
Germination % Arificially Dried	30	64			82	88	82		92	96	97	69
Starch Yield %	83.4	83.4	83.2	82.7	81.4	79.8	79.3	82.2	77.2	78.7	77.0	79.6
Protein in Starch, %	0.30	0.36	0.35	0.37	0.37	0.40	0.41	0.34	0.51	0.53	0.72	0.60
Protein in Gluten	36.7	40.6	37.3	37.4	32.9	37.5	38.0	33.2	39.5	40.1	37.0	38.9

1) No. 37 was a sample grade yellow milo ("toasted odor" otherwise No. 1) after drying all other samples were No. 1 yellow mild after drying.

Sorensen et al. (1949)

TABLE 4.3.1.3d

FUEL EFFICIENCY OF ARTIFICIALLY DRIED SORGHUM				
VARIETY	M.C. IN	M.C. OUT	DAT (°C)	EFFIC. (KJ/Kg)
Early Hegari				
No. 5	17-20	11-13	51.7	4660
6	17-20	11-13	65.6	4300
7	17-20	11-13	79.4	4080
8	17-20	11-13	93.3	3700
18	17-20	7-9	65.6	8680
20	17-20	7-9	93.3	5410
Martin				
No. 25	21-26	11-13	51.7	4230
27	21-26	11-13	79.4	5080
28	21-26	11-13	93.3	3710
29	17-20	11-13	51.7	8190
30	17-20	11-13	65.6	4360
31	17-20	11-13	79.4	3770
32	17-20	11-13	93.3	4330
37	21-26	7-9	51.7	8750
39	21-26	7-9	79.4	5060
40	21-26	7-9	93.3	5840
41	17-20	7-9	51.7	9430
44	17-20	7-9	93.3	7090
46	14-16	7-9	65.6	7310
47	14-16	7-9	79.4	7030
48	14-16	7-9	93.3	6090
50	21-26	11-13	110.0	4590

Sorensen et al. (1949)

4.3.2 SUMMARY

It appears that corn is more sensitive to breakage, germination and wet milling damage during artificial drying than sorghum. The major grain dryer parameters which determine corn wet millability are grain M.C., dryer design, grain temperature history, airflow rate, DAT, rate of drying and drying time. The design of the dryer is probably the most important parameter. Evidence shows that the type of drying system determines the safe DAT.

Sorensen et al. (1949) showed that the M.C. and the drying time have a greater effect on the wet milling characteristics of sorghum than DAT (110°C or less).

A DAT above 110°C and its effect on the wet milling has not been investigated previously. Nellist (1982) reported that the grain temperature history is the determining factor in grain quality not the DAT. The CC/CF dryer can employ DATs of 176.7°C without raising the grain temperature above 93.3°C. Thus, it seems reasonable to believe DATs greater than 110°C CC/CF can be used to dry sorghum for wet milling purposes.

Watson (1967) reviewed the wet milling sorghum industry. He reported that M.C. at harvest is ordinarily 14-18% and for this reason sorghum lots damaged by high temperature drying are infrequently encountered. He had 17 years of wet milling experience with sorghum when he made this statement. Thus it appears that M.C. and time of exposure to high DATs are the most critical parameters in producing quality sorghum for wet milling.

CHAPTER 5

OBJECTIVES

The objectives of this thesis are:

(1) To evaluate a sorghum CC/CF dryer for performance (moisture reduction, grain temperature and fuel efficiency).

(2) To evaluate the quality of CCF dried sorghum for germination and wet milling characteristics (starch yield and protein content in the starch).

(3) To verify the MSU CCF simulation model with experimental data.

(4) To design a commercial CCF dryer using the MSU simulation model.

CHAPTER 6

SIMULATION

Grain drying simulation programs, after being verified by experimental data, are useful in predicting grain drying results, in finding optimum design parameters to reduce energy costs and improve grain quality, and in reducing costly experimentation during grain dryer design. Simulation programs based on uniform diffusion in a spherical kernel have been developed for the single stage CC/CF dryer (Baughman et al., 1973) and for the multistage CC/CF dryer with tempering (Brook and Bakker-Arkema, 1978). Dynamic programming has been used to evaluate optimum design parameters for energy efficiency and grain quality in the single stage CC/CF dryer (Farmer, 1972) and the multistage CC/CF dryer (Brook and Bakker-Arkema, 1980). Borsum et al. (1982) described a control system which monitored grain temperature and adjusted the grainflow rate. The monitor was able to control the grain flow and thus control the outlet grain temperature. Bakker-Arkema and Schisler (1984a) verified a counterflow simulation model which accurately described counterflow cooling of grain.

Deep-bed dryer simulation models have been developed at Michigan State University (MSU) by Bakker-Arkema et al. (1974). They are based on mass and energy balances and have the following assumptions:

(1) the volume shrinkage of the bed is negligible during drying;

(2) the temperature gradient within an individual particle is negligible;

(3) the particle to particle conduction is negligible;

(4) the airflow and grainflow are plug-type (no wall effects);

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

(6) the bin or dryer walls are adiabatic, with negligible heat capacity;

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

(8) accurate thin-layer, moisture equilibrium isotherm and latent heat of vaporation equations are known.

6.1 MODELS

Both the concurrentflow and counterflow stages of the CCF dryer are described by a set of four ordinary differential equations (Bakker-Arkema et al., 1983c):

(1) $dT/dx = -i\ ha\ (T-\theta)/(G_aC_a+C_ac_vW)$

(2) $dO/dx = (ha(T-\theta)/(G_pc_p+G_pc_wM)-i(h_{fg}+C_v(T-\theta))G_a/(G_pc_p + G_pc_wM)(dW/dx)$

(3) $dW/dx = (-G_p/G_a)(dW/dx)$

(4) $d\bar{M}/dt =$ an appropriate diffusion-type thin-layer equation

The four dependent variables are: air temperature (T), grain temperature (θ), absolute humidity (W), and dry basis grain moisture (M). The concurrent flow equations have the index (i) positive, while the counterflow equations have the index (i) negative. The boundary conditions for the grain are the same in both flows:

(5) $M(o) = M_{in}$ and $\theta(o) = \theta_{in}$

The boundary conditions for the air differ. For concurrent flow:

(6) $T(o) = T_{in}$ and $W(o) = W_{in}$

For counterflow:

(7) $T(L) = T_{in}$ and $W(L) = W_{in}$

The specific heat of the grain is (Rao and Pfost, 1980):

(8) $Cp = 0.9881 + 2.6377\ \bar{M}$

The latent heat is (Brook and Foster, 1981):

(9) $h_{fg} = [2502.1 - 2.386\ \theta]\ [1 + 1.006\ \exp\ (\ -19.650\ \bar{M})]$

The convective heat transfer coefficient is (Brook and Foster, 1981):

(10) $h' = [0.4365/r] - [r\ Ga]^{0.66}$

The grain velocity is computed from:

(11) $Vw = G_p\ [1 + \bar{M}]/Rw$

where according to Rao and Pfost (1980):

(12) $Rw = 816.7 - 415.2\ \bar{M}/[1 + \bar{M}]$

Several additional properties and solution parameters are used: the radius r = 0.0014, the specific area a = 1060, the dry grain density Rg = 772.0, C_v = 1.884, C_w = 4.187, and C_a = 1.013. The solution techniques for the concurrent and counterflow models are explained in Bakker-Arkema et al. (1983a).

6.2 THIN-LAYER DRYING EQUATIONS

Two thin-layer drying equations are available for use in the CC/CF simulation model.

(1) The first assumes that sorghum is spherical. A diffusion equation in spherical coordinates is used as the thin-layer drying equation.

$$MR = (6/\pi^2) \sum_{n=1}^{\infty} (1/n^2) \ \mathrm{Exp}\,[-n^2\pi^2\, Dt/r^2]$$

where: MR is the moisture ratio (unitless), the radius of sorghum (r) is in meters, the time (t) is in hours, and the diffusion coefficient by Suarez et al. (1980) is determined by:

$D = 0.001253 \ \exp\,[-3788.0/(273.0 + \Theta)]$.

The diffusion coefficient (D) is in m^2/hr. It was evaluated from 20°C to 60°C.

(2) The Paulsen and Thompson (1973) thin layer equation (an empirical drying equation) is:

$t = A \ln Mr + B\,(\ln Mr)^2$

where:

MR = moisture ratio, = (M-Me)/Mo-Me)

M = moisture, content, dry basis decimal

Me = equilibrium M.C., dry basis decimal

Mo = original M.C., dry basis decimal

Apt = A = $25.87 + 0.3354Zpt - 0.001075Zpt^2$ for 26.7 to 71.1°C

A = 0.54-0.0017Zpt for 71.1 to 115.6°C

Zpt = 1.8 T + 32

T = drying air temperature, °C

B = Bpt = 30.35 EXP(-0.0180Zpt)

This equation has an operating DAT range up to 115.6°C (240°F). For CCF drying which normally uses DATs much higher the equation must be extrapolated to obtain drying data.

Figure 6.2a shows the drying behavior of six field crops at a constant relative humidity (60%) and temperature (25°C) for one hour. Figure 6.2b shows the drying behavior of the same crops but at a different temperature (85°C). Several conclusions can be drawn from Figures 6.2a and 6.2b:

(1) the rate of drying increases with temperature,

(2) the drying rate of grains differ with kernel size, and

(3) the drying rate levels off near the EMC.

The thin layer equations used for figures 3 and 4 are:

(1) for corn (Misra and Brooker, 1978),

(2) for wheat and barley (O'Callaghan et al., 1971),

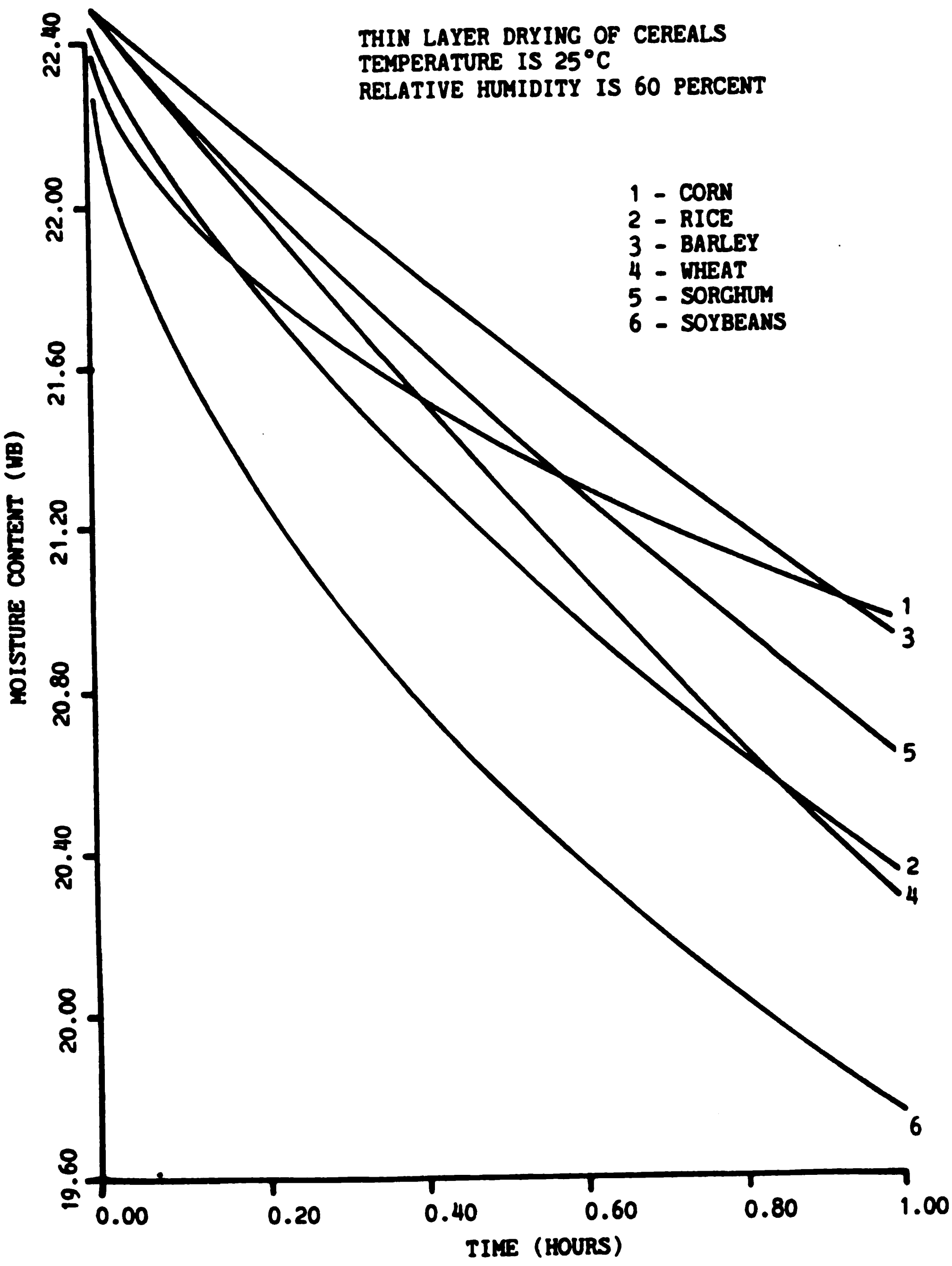

Figure 6.2a. Thin layer drying of cereals.

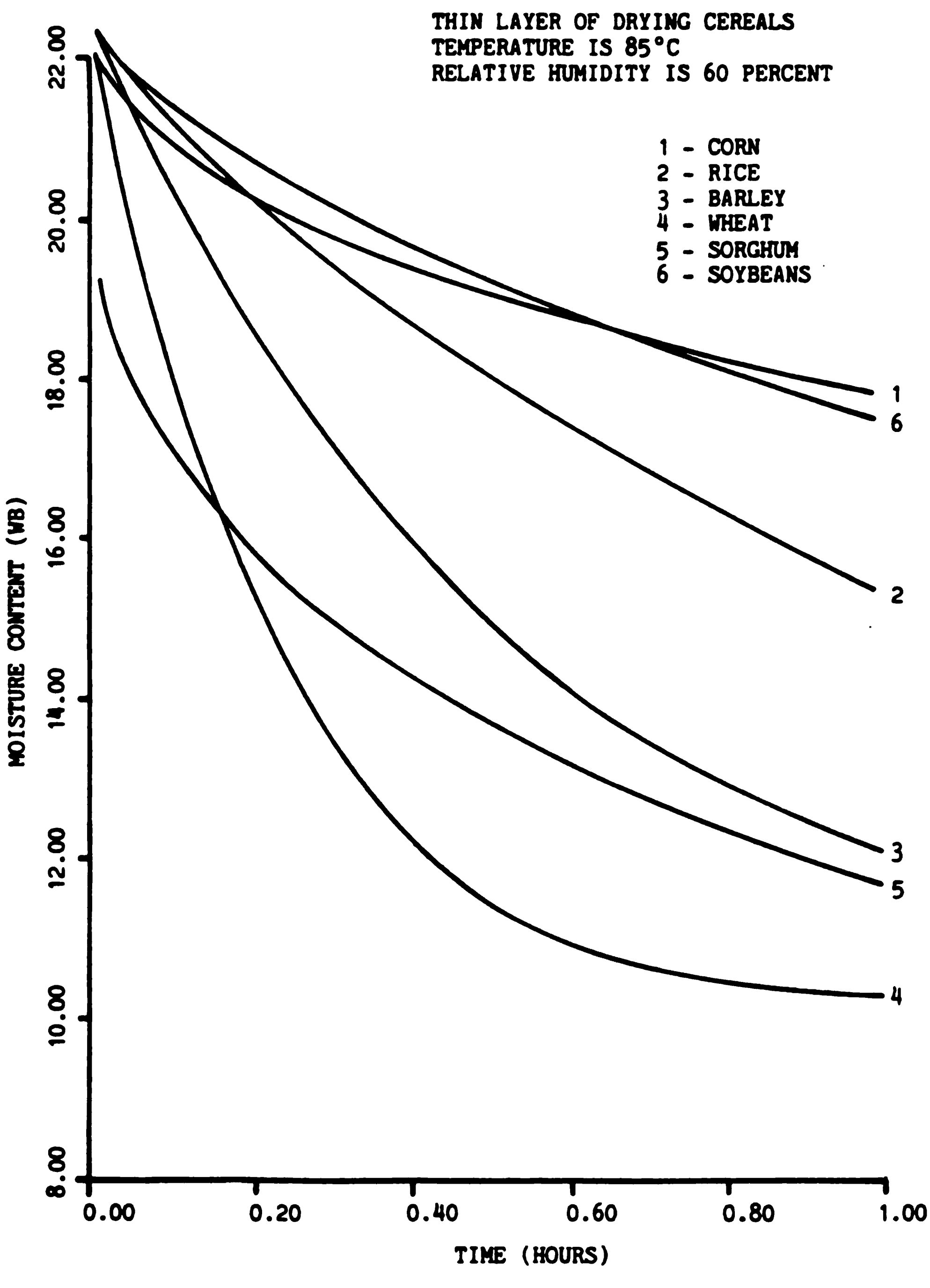

Figure 6.2b. Thin layer drying of cereals.

(3) for sorghum (Paulsen and Thompson, 1973),

(4) for soybeans (White et al., 1978), and

(5) for medium-grain rice (Wang and Singh, 1978).

6.3 EQUILIBRIUM MOISTURE CONTENT

The equilibrium moisture content (EMC) determines the minimum moisture content to which grain can be dried. It is dependent upon the humidity and temperature conditions of the environment as well as on the species, variety, maturity, and pre-treatment of the grain (Brooker et al., 1974). The EMC of a grain is defined as the moisture content of the material after it has been exposed to a particular humidity and temperature for an infinitely long period of time.

The equilibrium moisture content equation for sorghum is (Pfost et al., 1976):

$$Me = 0.39144-0.05097\ (\ln\ (-1.987)(\theta+102.849)\ln\ (\phi))$$

6.4 STATIC PRESSURE/AIRFLOW EQUATIONS

Four equations are available for determining the airflow rate (V) from the static pressure:

(1) Shedd (1953) data was fitted into equation form by Hukill and Ives (1955) and is the following:

$SP = (6.8569\ V^2 L)/\ln\ (1.0+0.1608V)$

where:

SP = static pressure, Pa

V = air velocity, m/min

L = bed depth, m

(2) The Chung et al. (1984) equation is given in section 2.3.2.

(3) The Haque et al. (1982) equation has the following form:

$Sp_H = A_H V + B_H V^2 - C_H M_H V$

where:

SP_H = pressure drop per meter depth of grain Pa/m

V = air velocity, m/s

M_H = grain moisture content, % w.b.

A_H, B_H and C_H = constants

A_H = 3253.11, B_H = 7911.3, C_H = 72.5

(4) The Jindal and Thompson (1972) equation is:

$\ln(V/3.2808) = 0.7737\ \ln\ (SP_J/4.0186) + 3.8872$

where:

V = air velocity, m/min

SP_J = static pressure, KPa/m

The simulation model uses equation (1). Equations (1), (2) and (3) all give similar results. Equation (4) gives airflow rates which are much higher than (1), (2), and (3). The reason for this will be discussed later.

CHAPTER 7

EXPERIMENTATION

This section discusses the CC/CF drying procedures and the tests to evaluate the quality of CC/CF dried sorghum.

7.1 PILOT-SCALE CC/CF DRYING (PROCEDURE AND INSTRUMENTATION)

A pilot-scale one-stage CCF dryer with a counterflow cooler was employed (see Figure 7.1a) to test the feasibility of CCF drying of sorghum. The dryer is a small version (5.63m high) of the commercial CCF dryer described by (Bakker-Arkema et al., 1983). The grainbed area is 0.813m X 0.813 X m (0.660m^2), the drying bed depth 0.73m and the cooling bed depth 0.30m. Wet grain and air are mixed on the drying floor containing four 0.2m diameter tubes (see Figure 7.1b).

Two Caldwell centrifugal fans are used for heating and cooling. The heating fan is a C18-732 model with 5.6 KW (7.5 HP) motor, the cooling fan is a C15-3 model with 2.2KW (3 HP) motor. Airflow/static pressure data was available for the fans [heating fan: static pressures of 0.498 - 3.484 KPa (2.0 - 14.0 inches of water) with airflow rates of 118.1 - 69.9 m^3/min (4170 - 2470 CFM) respectively;

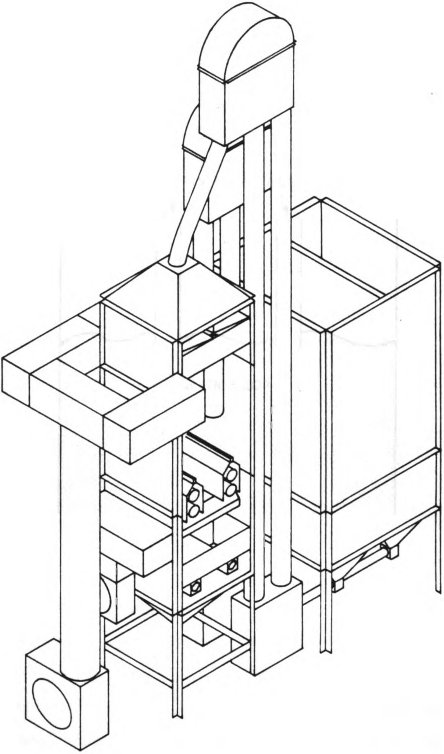

Figure 7.1a One-stage pilot-scale concurrentflow dryer (Bakker-Arkema et al., 1983a).

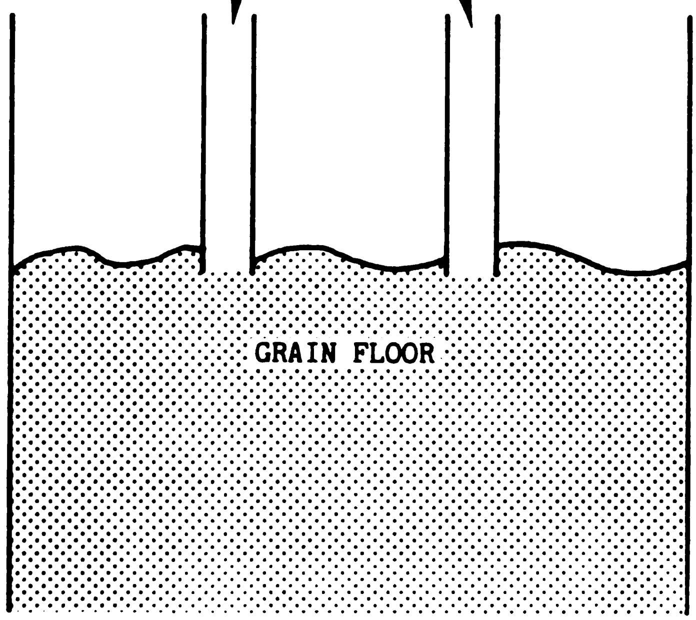

Figure 7.1b Pilot-scale CCF drying floor.

cooling fan: static pressures of 0.249 - 2.240 KPa (1.0 - 9.0 inch of water) with airflow rates of 72.5 - 38.8 m^3min (2560 - 1370 CFM)].

Grain-speed, airflow rate, and drying air temperature can be controlled independently. Grain velocity was controlled between 1.5 and 7.6m/hr, airflow rate at the equivalent of 7.6-33.5cm (3-13.2 in) W.C. (for sorghum 6.1-37.0m^3/min/m^2 (20-121 CFM/ft^2), and drying air temperature between 65 and 288°C.

Two storage hoppers are attached to the dryer. One was used as a wet holding bin and the other to simulate tempering.Tempering was employed between drying stages. The hot dried grain leaving the dryer would be loaded into the tempering hopper for 45-90 minutes before re-entering the dryer. The hot grain was allowed to temper during this period.

The experimental tests were conducted in Grand Island, Nebraska with sorghum obtained from a local elevator. The initial moisture content of the sorghum was 15-16% (w.b.) No record was available of the variety (or mix of varieties).

The following parameters were determined in the performance evaluation of the CCF dryer:

(1) the drying capacity (kg/hr);

(2) the moisture content before and after drying;

(3) the initial and final sorghum temperature and the sorghum temperatures throughout the dryer and the storage hopper;

(4) the drying air temperature along with the dry bulb and wet bulb temperatures of the ambient and exhaust air;

(5) the initial and final test weight;

(6) the static pressures (and thus the airflow rates);

(7) the energy consumption; and

(8) the initial and final sorghum quality determined by germination, wet milling yield, and protein in starch analysis.

The dryer has a holding capacity of approximately $1.18 m^3$ ($41.59 ft^3$). Each test simulated two or three-stage drying followed by cooling. The beginning of a new drying stage is determined by the change of grain temperature in the grainflow tubes. A new stage coming out of the dryer is determined by grainflow rate and dryer holding capacity. The discharge rate (Kg/hr) was calculated by making time-weight measurements of discharged grain, taken during each drying run.

The M.C. of the sorghum samples was measured with a Dickey-john GAC II meter and confirmed with an oven method (130°C for 18 hrs.) (Baxter and Hahn, 1978). Samples were collected every 10-30 minutes.

The initial and final sorghum temperatures were determined with the Dickey-john GAC II meter. Figures 7.1c and 7.1d show the location where air and grain temperatures were measured in the grain dryer.

The temperatures were measured every 10-15 minutes with copper-constantan thermocouples in conjunction with a manual potentiometer. The drying air temperature was measured with an iron-constantan thermocouple.

Wet and dry bulb exhaust and ambient temperatures were measured by a sling psychrometer and with copper-constantan thermocouples. All thermocouples were calibrated in boiling water and in ice water.

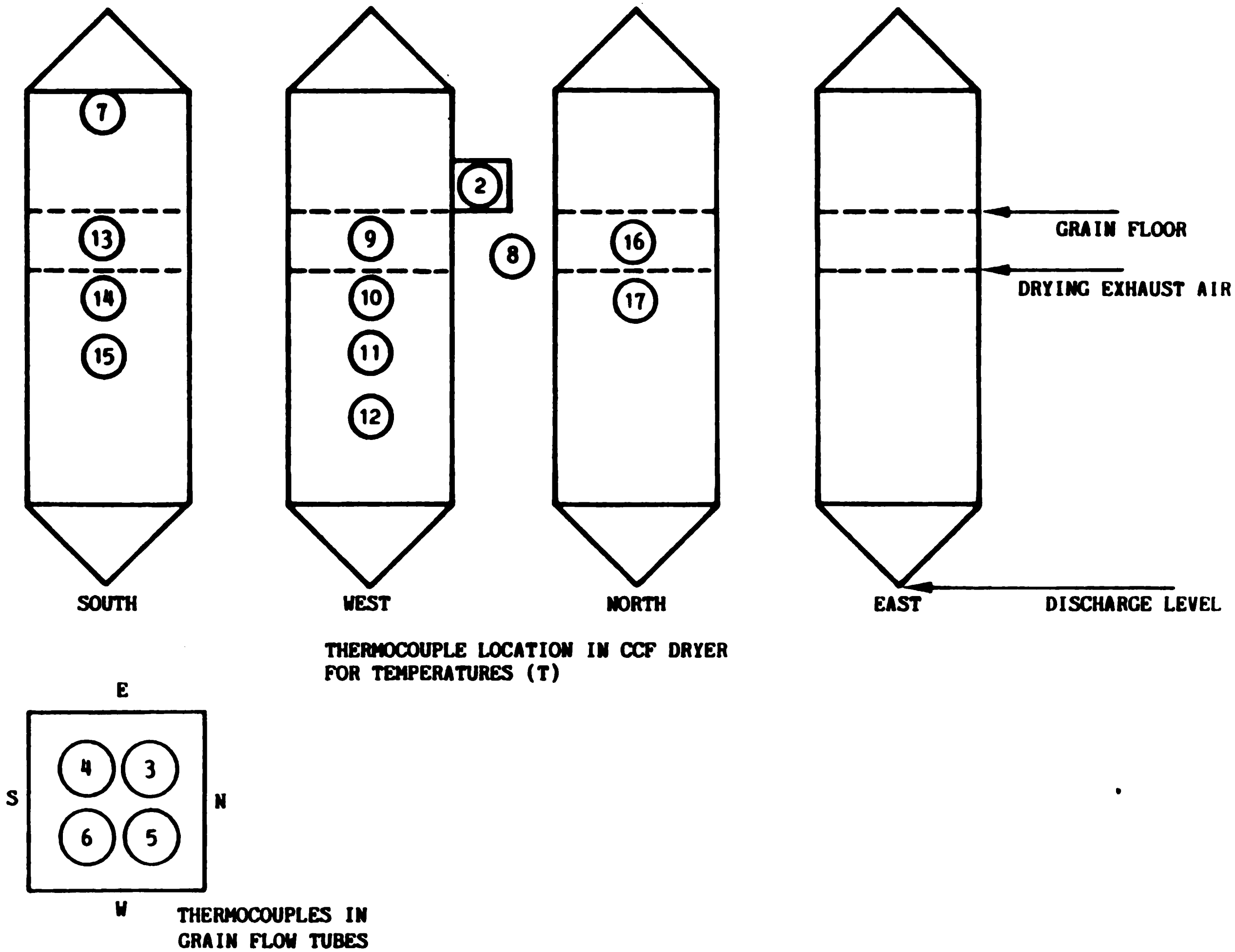

Figure 7.1c 7.1d Thermocouple location for temperatures in pilot-scale CC/CF dryer.

FIGURE 7.1d

THERMOCOUPLE LOCATION FOR TEMPERATURES (T)

IN PILOT-SCALE CC/CF DRYER[1]

#1	Ambient air T
#2	Drying air T in heat duct
#3,4,5,6	Grain flowtube (GFT) T's
#7	Inlet grain T
#8	Exhaust drying air T
#9	Drying bed T grain (0.394m below GFT but only covered with 0.241m of grain when checked)
#10	Exhaust grain T (0.953m below GFT)
#11	Cooling bed grain T
#12	Below cooling bed grain T
#13	Drying bed grain T (0.254m below GFT but only covered with 0.076m of grain when checked.)
#14	Exhaust grain T (0.932m below GFT)
#15	Cooling bed grain T
#16	Drying bed grain T (0.406m below GFT but only covered with 0.267m of grain when checked.)
#17	Exhaust grain T (0.914m below GFT)

[1] Drying bed depth, 0.732m

Static pressures within the inlet air heating and cooling ducts were measured with pressure gauges. The air velocities (m/min) were calculated from the Haque et al. (1982) equation for static pressure (see section 6.4). The values for the air velocities were confirmed by the Chung et al. (1984) and the Hukill and Ives (1955) static pressure equations (see section 6.4).

7.2 THE FUEL EFFICIENCY CALCULATION

The gas flow meter which was attached to the dryer did not function properly. Therefore, the fuel consumption was determined by the following manner:

(1) $q = CaGa(To-Ti) + CpGp(\Theta o-\Theta i) + h_{fg}\,(Wi-Wo)$

(2) $\text{Efficiency} = q/(Wi-Wo)$

Where

C = Specific Heat KJ/Kg°C

G = Mass Flow Kg/hr

To = Exhaust Air Temperature (°C)

Ti = Ambient Air Temperature (°C)

Θo = Grain Temperature Out (°C)

Θi = Grain Temperature In (°C)

h_{fg} = Latent Heat Of Sorghum (KJ/Kg)

(Wi - Wo) = Loss Of Water In Grain (Kg/hr)

^{a} = Air

^{p} = Product

^{i} = in

^{o}= out

The airflow was calculated by the following equation:

(3) Ga = (Velocity of air) (Area of drying bed) (Density of air)

Equations 1 - 3 were used to determine the efficiency of each drying stage and the overall fuel efficiency. Equation (1) will be called the latent heat equation.

7.3 GRADE OF SORGHUM

The grade of sorghum was determined using the standard methods (USDA, 1974).

7.4 GERMINATION DETERMINATION

Germination tests were conducted for the inlet and outlet samples of sorghum. The tests were performed at the Michigan Crop Improvement Association Laboratory (East Lansing, MI). For each sample duplicates of 100 seeds (treated with the fungicide Captan) were employed. The seeds were placed on saturated (water) blotter paper in a germination chamber for 10 days at 25°C and 80% relative humidity. The first count was taken at 5 days and the second at 10 days. Germination for each seed was determined as either (1) strong root development, (2) weak root development, or (3) no root development. The strong and weak root counts were added together for the total germination percentage. Weak germination had a root of less than one 2.5 cm.

7.5 WET MILLING

The wet milling procedure was a modification of two published procedures: (USDA, 1964) and (Neryng et al., 1983).

7.5.1 EQUIPMENT AND REAGENTS

(1) Water bath (temperature control),

(2) 50 ml centrifuge tubes with tops,

(3) plastic container cups with lids,

(4) blender (3 blades),

(5) International centrifuge,

(6) 3 sieves (stainless steel) and collector,

40 mesh (.420 mm)

200 mesh (.074 mm)

270 mesh (.053 mm)

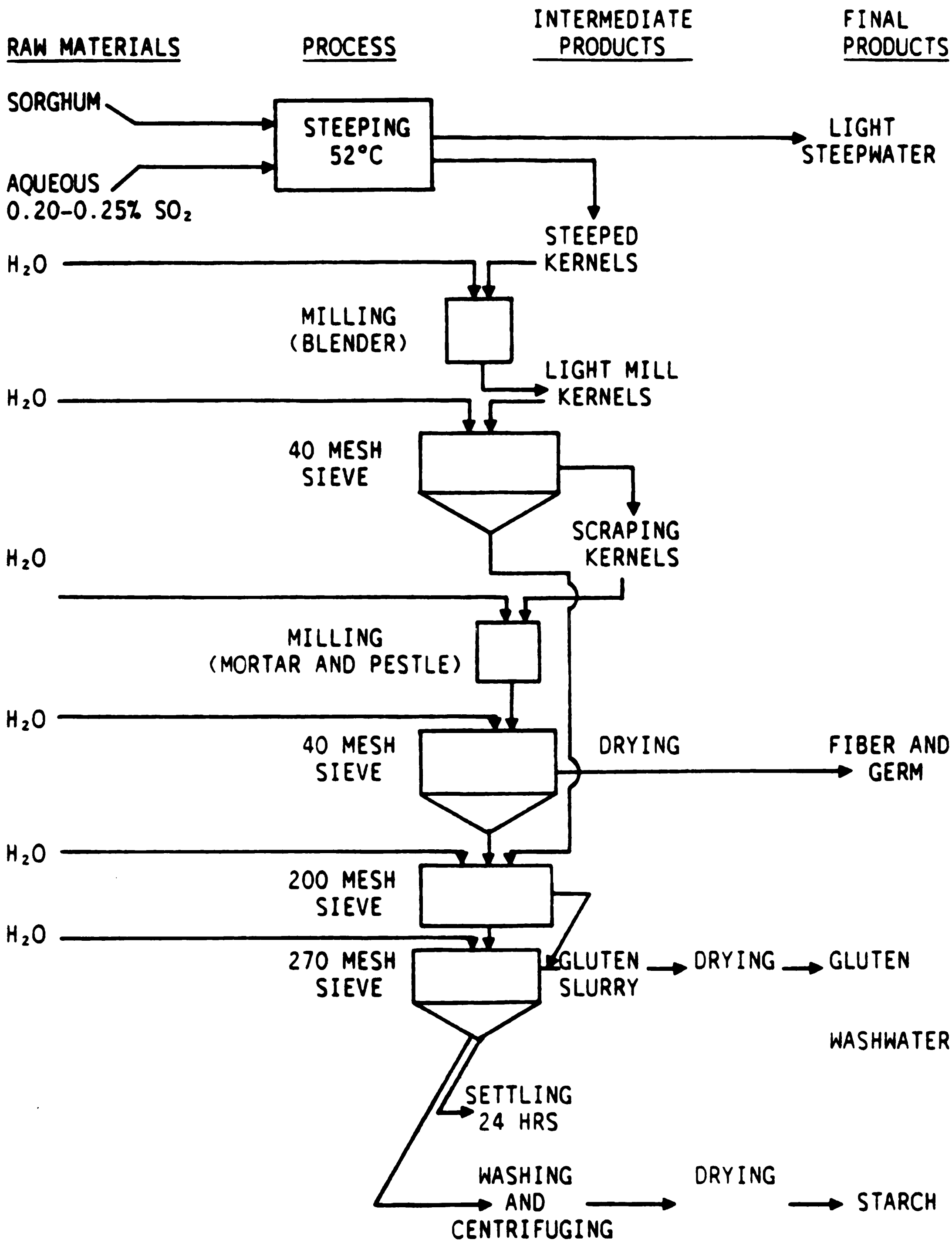

Figure 7.5.2 Wet milling procedure.

(7) mortar and pestle,

(8) drying oven,

(9) 500 ml erlenmeyer flasks,

(10) settling buckets,

(11) distilled water,

(12) Na_2SO_3 bisodium sulfate.

7.5.2 STEEPING

(1) 50 gram sorghum samples are weighed out (w.b.);

(2) 0 .2 - .25% sulfur dioxide (SO_2 solution is made by mixing 4.919 g of Na_2SO_3 with 1000 ml of distilled water;

(3) 150 ml of SO_2 solution is mixed with the 50g sorghum sample in a 500 ml erlenmeyer flask;

(4) The flasks are placed in a 50 - 52°C water bath for 48 hours;

(5) After 48 hours steeping, the flasks are removed and drained of liquid.

7.5.3 MILLING

(1) The steeped sorghum is ground in a blender with distilled water (200 ml) for 1 1/2 minutes. Every 30 seconds the blending is stopped to wash the sides of the blender.

(2) The ground mixture is poured on to the sieves. The sieve arrangement from the top is the #40 mesh, #200 mesh, #270 mesh and the collector. Distilled water is poured on to free the gluten and the starch. The residue on the #40 mesh sieve is ground with a mortar and pestle and poured again on to the #40 mesh sieve.

(3) The fiber is collected from the #40 mesh sieve.

(4) Gluten and starch caught by the 200 and 270 mesh sieves were washed with water to more completely separate the starch (see figure 7.5.2).

(5) Starch and gluten which have passed to the collector are placed in a settling container (24 hrs).

(6) Steps 1 - 4 are repeated a second time. The blending period is 3.0 minutes. The mortar and pestle are not used.

7.5.4 STARCH ISOLATION

(1) After settling for 24 hrs, the water is drained off and the gluten-starch mixture is centrifuged in 50 ml tubes for 10 - 15 minutes at 2000 RPM.

(2) The dark gray gluten is scraped off; the starch on the bottom is rewashed and centrifuged until totally cleaned of gluten.

7.5.5 STARCH YIELD

(1) The cleaned starch and other products are air dried for 2 days at 51.7°C (125°F). The starch is weighed.

(2) A small sample of the starch and a grain sample are oven dried at 130°C for 18 hours to determine the M.C. (d.b.).

(3) The yield is determined by:

Yield = (grams of starch)(dry weight)(100%)/(grams of grain)(dry weight)

7.6 PROTEIN IN THE STARCH ANALYSIS:

A Macro-Kjeldahl Method was used to determine the protein in the starch (AOAC, 1975).

7.6.1 REAGENTS

(1) H_2SO_4

(2) $CuSO_4/K_2SO_r$ mixture

(3) 4% boric acid

(4) 50% Na OH

(5) Zinc (mossy)

(6) 0.025 N HCL.

7.6.2 PREPARATION:

(1) A 1 - 3g sorghum starch sample with a known M.C. is weighed out on.

(2) The sample is placed in a Kjeldahl flask. Also, 8 - 9g of $CuSO_4/K_2SO_4$ mixture, 2 - 3 boiling beads and 25 ml of H_2SO_4 are added to the Kjeldahl flask. Each starch sample is run in duplicate.

7.6.3 DIGESTION

(1) The flasks are boiled on digestion burners and turned periodically (every 30 minutes) until the liquid becomes bluish-green (about 1 1/2 to 2 hrs later). When the

bluish-green color appears, boiling is continued for another 30 to 45 minutes (almost clean in color).

(2) At this point the digested product can be left for several days before completing the test.

7.6.4 DISTILLATION

(1) 250 ml of distilled water is added to the flasks slowly.

(2) 60 ml of 50% NaOH is slowly added to the flask along with a teaspoon of mossy zinc.

(3) A beaker with 25 ml of 4% boric acid and 3 - 9 drops of indicator is placed under each condenser tube.

(4) The flasks are placed on the distillation apparatus.

(5) When 200 ml of gluid has been collected in the beaker under the condenser tube, the distillation is stopped.

(6) Each beaker is titrated with .IN HCL until the solution turns faintly pink. The number of ml of 0.1 N HCL used is recorded.

7.6.5 CALCULATIONS:

% protein = 1.4 (HCL normality)(ml HCL)(6.25)/(sample weight)(DM decimal)

Where: DM = Dry Matter   Sample Weight = Grams

CHAPTER 8

RESULTS AND DISCUSSION

This section discusses the experimental and simulation results. The experimental results will be presented first and then compared with the simulation results.

8.1 EXPERIMENTAL RESULTS

8.1.1 CONCURRENT/COUNTERFLOW DRYER

Table 8.1.1a lists the average and maximum temperatures recorded during the three drying tests with a pilot-scale CC/CF dryer. The location of the thermocouples is given in figures 7.1c and 7.1d. Thermocouple #13 had the highest average and maximum grain temperatures since it is located closest to the surface of the drying bed (0.076m). At the bottom of Table 8.1.1a the thermocouples are grouped according to general location in the dryer.

Thermocouples #3 - 6 (grainflow tube temperatures) were used to determine when a new drying stage enters the drying bed. Thermocouples #9, 13 and 16 were employed to determine drying bed temperatures.

Grain temperatures were found to be far below the drying air temperatures during CCF drying (thermocouple #13 versus #2). This is evidence that the conventional recommendations for safe drying air temperatures (DATs) do not apply to CCF drying. A CCF dryer is able to operate at higher DATs than conventional dryers of crossflow design and still give gentle treatment to the grain. Test #6 is an excellent example (stage 1); a DAT of 217°C only produced a maximum grain temperature of 85.6°C (thermocouple #13). Future safe drying air temperatures must take into account dryer design because it is the grain temperature that determines the quality of the grain.

Grain temperatures were found to decrease as the grain passes through the CC/CF dryer. The hottest air encountered the coldest grain and then both air and grain decrease slowly in temperature (see figure 3.1a). This helps to reduce stress cracks and subsequent breakage during handling of grain.

Table 8.1.1b presents the additional data obtained during the three experimental drying tests. Test #3 had the lowest grain outlet M.C. (9.4%) and test #6 the highest (12.6%). The ambient air temperatures were freezing or close to freezing. This resulted in higher fuel consumption to heat the air to the drying air temperature.

TABLE 8.1.1a

EXPERIMENTAL* TEMPERATURES (^{o}C) IN PILOT-SCALE CC/CF DRYER DRYING SORGHUM

TEST	# 1 Ave	2 Ave	3-6 Ave	7 Ave	8 Ave	9 Ave	9 Max	10 Ave	11 Ave	12 Ave	13 Ave	13 Max	14 Ave	15 Ave	16 Ave	16 Max	17 Ave
# 3																	
Stage 1	4.4	163	16.0	16	37.8	75.5	77.2	72.3	65.0	66.9	78.2	81.6	----	69.7	64.5	67.2	----
Stage 2	4.4	163	43.0	43	51.7	82.8	85.0	78.2	75.6	73.3	92.5	96.0	----	70.9	73.2	74.4	----
Stage 3	4.4	163	48.0	48	56.4	87.9	90.5	86.1	74.7	20.6	92.6	93.3	----	75.3	72.4	73.9	----
# 5																	
Stage 1	-1.1	146	10.0	10.0	33.9	71.7	73.3	69.4	62.8	54.4	86.3	90.0	62.2	61.7	66.1	67.8	60.6
Stage 2	-1.1	118	38.0	38.0	43.3	66.3	67.2	63.8	59.2	49.7	78.9	79.4	61.3	57.8	59.4	60.0	54.7
Stage 3	-1.1	85	37.0	37.0	41.1	56.1	57.8	54.4	51.3	37.8	61.7	63.3	50.0	45.4	49.4	50.0	48.9
# 6																	
Stage 1	0.0	217	13.0	13.0	38.3	67.3	71.1	66.1	61.2	60.0	83.8	85.6	68.3	66.1	64.4	66.1	66.1
Stage 2	0.0	146	49.0	49.0	49.0	65.0	66.7	62.8	57.7	48.9	78.2	79.4	60.0	60.7	58.8	61.0	57.2

* #1 Ambient air temp
#2 DAT
#3,4,5,6 Grain flowtube temp - inlet
#7 Inlet grain temp
#8 Exhaust air temp
#9,13,16 Drying bed grain temp
#10,14,17 Exhaust grain temp
#11,15 Cooling bed grain temp
#12 Below cooling bed grain temp

temperature. Test #6 had the highest grainflow rates and the highest DATs. Test # 5 had the lowest grainflow rates and the lowest DATs. Grainflow rate reflected the DAT. The outlet grain temperatures were below 54.4°C (130°F) which indicated gentle drying treatment.

The air velocity was first computed with the static pressure equation of Haque et al. (1982) and checked with the Chung et al. (1984) equation. In addition, the Hukill and Ives (1955) and the Jindal and Thompson (1973) equations were used. Table 8.1.1c shows that the Chung et al. and Bakker-Arkema et al. equations agree with the Haque et al. equation. However, the Jindal and Thompson equation gives air velocities which are much higher. All four equations must be extrapolated beyond their intended range. The Jindal and Thompson (1973) equation was disregarded for its failure to duplicate the Shedd (1953) data and the other equations.

TABLE 8.1.1b

EXPERIMENTAL PILOT-SCALE CC/CF SORGHUM DRYING DATA

Test No.	3	5	6
Ambient Air Temp (°C)	4.4	-1.1	0.0
Relative Humidity (%)	60	--	--
M.C. in (% w.b.)	15.9	15.8	15.9
Initial Grain Temp (°C)	13.3	12.2	13.3
[1]Static Pressure (Pa)	3110.5	3110.5	3284.7
First Stage			
Inlet Air Temp (°C)	162.8	146.1	216.7
Airflow Rate (m^3/min m^2)	36.5	36.5	37.7
M.C. out (% w.b.)	14.2	13.8	14.2
[3]Grainflow Rate (Kg/hr/m^2)	2569	2160	3637
Outlet Sorghum Temp (°C)	46.1	46.1	51.7
Second Stage			
Inlet Air Temp (°C)	162.8	118.3	146.1
Airflow Rate (m^3/min m^2)	36.0	36.1	37.4
M.C. Out (% w.b.)	11.0	12.3	--
Grainflow Rate (Kg/hr/m^2)	2569	2301	3746
Outlet Sorghum Temp (°C)	51.7	48.9	--
Third Stage			
Inlet Air Temp (°C)	162.8	85.0	--
Airflow Rate (m^3/min m^2)	35.5	35.8	--
M.C. out (% w.b.)	--	--	--
Grainflow Rate (Kg/m/m^2)	2569	2280	--
Cooling Stage			
Inlet Air Temp (°C)	4.4	-1.1	0.0
[4]Airflow Rate (m^3/min m^2)	24.6	24.4	24.8
Final Sorghum Temp (°C)	39.4	28.9	35.0
Final M.C. (% w.b.)	9.4	11.3	12.6
[2]Static Pressure (Pa)	2364.0	2289.4	2289.4

[1] 3110.5 KPa (12.5 inch) and 3284.7 Pa (13.2 inch)
[2] 2364.0 KPa (9.5 inch) and 2289.4 Pa (9.2 inch)
[3] Grainflow (wet weight)
[4] Airflow rate calculated using Haque et al. (1982) static pressure equation.

TABLE 8.1.1c

EXPERIMENTAL* AIR VELOCITIES (M/min) CALCULATED FROM MEASURED STATIC PRESSURES ACCORDING TO DIFFERENT EQUATIONS

Test	Stage	Hague et al. (1982)	Chung et al. (1984	Hukill and Ives (1955) fitted equation	Jindel & Thompson (1973)
#3	1	36.5	36.9	34.0	53.3
	2	36.0	35.0	34.0	53.3
	3	35.5	33.9	34.0	53.3
#5	1	36.5	36.8	34.0	53.3
	2	36.1	35.8	34.0	53.3
	3	35.8	34.6	34.0	53.3
#6	1	37.7	38.3	35.2	55.6
	2	37.4	36.9	35.2	55.6

* Test #3 and #5 SP = 12.5" or 3110.5 Pa
Test #6 SP = 13.2" or 3284.7 Pa

8.1.2 FUEL EFFICIENCY CALCULATIONS

Table 8.1.2a contains the data for fuel efficiency calculations. Equations 1 - 3 in section 7.2 were used to calculate the efficiency. The latent heat equation (LHE) (equation 1, section 7.2) uses airflow rate, grainflow rate and the latent heat of evaporation (sorghum) to determine energy (KJ/hr) use.

The latent heat of evaporation and the specific heat equations for sorghum are found in section 6.1. The airflow rate (Kg/hr) was determined using equation 3 in section 7.2. The density of the air was calculated from data provided by Holman (1981).

The fuel efficiencies (KJ/KgH_2O) for the three tests were also calculated by using the amount of air heated in the burner. The following heated air equation (AE) was used:

$$q = CaGa\,[DAT - Ti]$$

The two methods of calculating the fuel efficiency result in similar values for the three tests as shown in Table 8.1.2b.

The fuel consumption (Table 8.1.2a) is lowest in test #3 (4922 KJ/kgH_2O) and #6 (4928 KJ/KgH_2O) which used high drying air temperatures; it is highest for test #5 which employed lower drying air temperatures (DATs). These three tests indicate that fuel efficiency improves with higher DATs.

An increase in fuel consumption (Table 8.1.2a) to 5189 KJ/kgH_2O in test #3, stage 3, is due to drying sorghum at a low M.C. (11.0% to 9.4%).

TABLE 8.1.2a

FUEL EFFICIENCY DATA* FOR THE PILOT-SCALE CC/CF DRYER

Test	Stage	Va	Ga	To-Ti	Cp	Ga	Oo-Oi	O	Hfg	Wi-Wo	DAT	EFFIC	MC IN	MC OUT	HEATED AIR EFFIC
3	1	36.5	1178.0	33.4	1.370	1697.0	32.8	63.8	2490	33.96	162.8	5900	15.9	14.2	5373
	2	36.0	1160.0	47.3	1.370	1697.0	8.7	73.9	2464	62.16	162.8	3677		11.0	2976
	3	35.5	1143.0	52.0	1.370	1697.0	9.8	75.6	2460	30.24	162.8	5189		9.4	6193
Ave.												4922			4847
5	1	36.5	1248.0	35.0	1.402	1427.0	33.9	68.0	2550	31.36	146.1	6013	15.8	13.8	5338
	2	36.1	1296.0	44.4	1.402	1520.0	10.9	64.2	2460	26.41	118.3	5520		12.3	6038
	3	35.8	1386.0	42.2	1.402	1506.0	-8.1	50.7	2493	17.94	85.0	5769		11.3	6904
Ave.												5767			6093
6	1	37.7	1078.0	38.0	1.426	2403.0	38.4	68.7	2431	48.10	216.7	6022	15.9	14.2	4590
	2	37.4	1278.0	49.0	1.426	2475.0	-14.0	57.2	2459	45.75	146.1	3834		12.6	4128
Ave.												4928			4359

* Ca = Specific heat of air (KJ/Kg^{o}C)
To = Exhaust air temp (0^{o}C)
Ti = Ambient air temp (^{o}C)
Cp = Sorghum specific heat
Cp = 0.9881 + 2.6377 M
Gp = Grainflow rate (Kg/hr) wet
Hf = Latent heat (KJ/Kg)
Va = Velocity air (m/s)
Ab = Area of bed (0.66064m^2)
M = M.C. (d.b.) ave, decimal
Oo = Grain temp out (^{o}C)
Oi = Grain temp in (^{o}C)
O = Average grain temp (^{o}C)
Wi-Wo = H_2O loss during drying (Kg/Hr)
O = $\frac{Oo + Omax}{2}$

Table 8.1.2b

EXPERIMENTAL FUEL EFFICIENCY

(KJ/KgH_2O) CALCULATIONS FOR TESTS #3, #5 AND #6.

Test #	Latent Heat EQ.	Heated Air EQ.	% Diff.
3	4922	4847	1.5
5	5767	6093	5.3
6	4928	4359	13.0

% difference (absolute value) ((LHE - AE)/AE)100%

Table 8.1.2c shows that:

(1) a large amount of energy in the first stage as opposed to the second stage is required for heating the grain;

(2) high DATs use more energy to heat grain than lower DATs in the first stage because of higher grainflow rates;

(3) the advantage of using high DATS (as opposed to low DATs) is realized in the second stage where less energy is used to heat the grain (compare test #3 to test #5); and

(4) there is an advantage in using high DATs with stage drying.

TABLE 8.1.2c

ENERGY NEEDED TO HEAT UP GRAIN IN THE FIRST AND SECOND STAGES

Test #	Stage	(LHE) Total Energy (KJ/hr)	Grain Energy[1] (KJ/hr)	% of Total Energy	EFF (KJ/KgH_2O)	EFF (KJ/Kg) Used For Heating Grain	DATs ^oC
3	1	202,695	76,256	37.6	5900	2218	162.8
	2	228,323	20,227	8.9	3677	327	162.8
	3	---[2]	---[2]	---	5189	--	162.8
5	1	196,443	67,831	34.5	6013	2074	146.1
	2	144,028	22,958	15.9	5520	878	118.3
	3	---[2]	---[2]	---	5767	---	85.0
6	1	297,082	131,600	44.3	6022	2668	216.7
	2	---[2]	---[2]	---	3834	---	146.1

1) Grain Energy = CpGp (Oo-Oi)

2) The cooler prevented measurement of outlet grain temperature from the drying stage.

The first stage is important for preheating the grain so that more efficient drying takes place in additional stages. Grainflow rate increases with an increase in the DAT to prevent excessive grain temperatures. The following conclusions may be drawn with CCF drying:

(1) high DATs increase the drying capacity and decrease fuel consumption;

(2) the second stage is more energy efficient than the first stage;

(3) grainflow rate can be used to control grain temperature at high DATs;

(4) fuel consumption increases when drying sorghum below 10 - 11% MC;

(5) grain temperature remains far below the DAT; and

(6) the energy efficiencies of a pilot-scale CC/CF dryer tests were calculated and verified.

8.1.3 GERMINATION AND USDA GRADE

Table 8.1.3 lists the germination data of the sorghum before and after the CC/CF dryer. A low germination is indicated for all samples. Runs #3, #5 and #6 have final stage germinations of 40.1, 50.9 and 51.6%, respectively, with an inlet viability assumed to be 100%. The relatively high germination indicates that the CC/CF dryer can treat the grain gently at high DATs. Table 8.1.1a

TABLE 8.1.3

GERMINATION AND USDA GRADING DATA FOR SORGHUM DRIED IN THE PILOT-SCALE CC/CF DRYER

TEST	GERM STRONG %	GERM WEAK %	GERM % OF INITIAL SAMPLE	[3] TEST WEIGHT #/BU	MC	DAMAGED [2,4] (FINES)	HEAT DAMAGED KERNELS	CORN + FINES %	USDA MIX CLASS GRADE[1] #
RUN #3									
Stage 1 In	45	7	100	58.2	15.9	2.6	0	7.4	2
Stage 1 Out	35	6	78.8	57.8	14.2	2.2	0	5.05	2
Stage 2 Out	15	4	36.5	57.5	11.0	3.1	0	8.2	3
Stage 3 Out	17	4	40.4	58.0	9.4	2.6	0	6.0	2
RUN #5									
Stage 1 In	48	9	100	58.4	15.8	2.4	0	4.7	2
Stage 1 Out	30	9	64.4	58.0	13.9	2.0	0	4.5	2
Stage 2 Out	--	--	50.9	57.5	12.3	2.2	0	5.4	2
Stage 3 Out	--	--	50.9	58.0	11.3	3.0	0	5.8	2
RUN #6									
Stage 1 In	57	4	100	57.7	15.9	2.0	0	6.4	2
Stage 1 Out	28	4	51.6	57.5	14.2	2.1	0	6.6	2
Stage 2 Out	29	3	51.6	57.5	12.6	2.6	0	4.9	2

[1] GRADE DETERMINED WITHOUT M.C.

[2] CORN DETERMINED WITH A 1/13 INCH SCREEN INSTEAD OF 5/64 INCH SCREEN (.00195m vs .00198m)

[3] MULTIPLY BY 12.874 TO OBTAIN Kg/M^3

[4] FINES ARE BROKEN KERNELS AND FOREIGN MATERIAL THAT PASS THROUGH A 1/13 INCH (.00195m) screen

shows the average grain temperature (see thermocouple #13) to be lower in Run #6 than in runs # 3 and # 5. The high grainflow rate (Table 8.1.1b) of run # 6 kept the grain temperature low despite the high DATs (216.7°C and 146.1°C). Run # 3 was lower in germination due to higher average grain temperature. Clearly, grain temperature history can roughly explain viability. The data in Tables 4.3.1.3a - c by Sorensen et al. (1949) also indicates that the grain temperature history can explain the viability (See Batch Nos. 9 - 12, 33 - 36, and 45 - 48).

An insignificant change in test weight (less than 1%) occurred during CCF drying of sorghum (Table 8.1.3). The test weights varied from 57.5 to 58.4 #/bushel (740.3 to 751.8 Kg/m^3).

The USDA grading of sorghum was determined (Table 8.1.3) without M.C. evaluation. All samples (except Run #3, stage 2 out) graded USDA mixed class grade #2 (see section 2.3.1). No significant increase in fines was detected due to CCF drying of sorghum.

8.1.4 WET MILLING DATA

The starch yield and protein percentage in the starch are presented in Table 8.1.4. Six samples (3 in and 3 out) were wet milled in triplicate. Protein in the starch was analyzed (in duplicate) in two ways; the entire sample and a sample without the top

(2mm) protein rich layer. The entire procedure from steeping to protein analysis required about 100 hours (18 samples).

The starch yield of the (in) samples averaged 1.77 to 3.17% higher than that of the (out) samples. Sorensen et al. (1949) reported that damage to wet milling by excessive artificial drying air temperatures reduced the starch yield (2 - 6% losses) and increased the protein content (doubled, 0.3% to 0.6%) in the starch. Table 8.1.4 shows a decrease in starch yield for the (out) samples.

However, the protein in the entire starch sample is higher for the (in) samples than the (out) samples (#3 and #5). The starch samples were washed 7 - 10 times to eliminate the protein; a visual judgment was made in determining whether to wash again. It is possible that the (in) samples of starch did not receive as thorough a washing as the (out) samples of starch. During each washing, some starch is lost in order to eliminate the protein. The original steeped grain samples weighed 50g (35g dry weight of starch, approximately); thus a loss of one gram by washing results in a 3% loss in starch.

Test #5 has the greatest difference in starch yield (in versus out) and whole sample protein content (in = 1.08% and out = 0.88%). Test #3 has the highest average and maximum grain temperatures (see table 8.1.1a, thermocouple #13). Thus, test #3 would be expected to show a higher loss of starch yield than test #5 (if the loss was due to heat damage from artificial drying). In using the starch yield limits in test #3 (Table 8.1.4), the minimum and maximum differences between the (in) and (out) samples of test #3 are:

Starch Yield	(IN) %	(OUT) %	DIFF %
Minimum	62.99	62.72	0.27
Maximum	64.99	61.72	3.27

TABLE 8.1.4

SORGHUM WET MILLING RESULTS

	STARCH YIELD	% PROTEIN INCLUDING TOP LAYER	% PROTEIN[1] WITHOUT TOP LAYER
RUN # 3			
IN	63.99 + 1.0	1.10	.84
OUT	62.22 + 0.5	1.00	.84
RUN # 5			
IN	63.17 +0.25	1.08	.86
OUT	60.00 +0.5	.88	.73
RUN # 6			
IN	61.50 + 1.0	.88	.97
OUT	59.61 + 0.3	.90	.79

[1] top layer (2mm)

The minimum difference is only 0.27% in starch yield; the maximum is 3.27%. The minimum difference suggests that no starch yield loss occurred in CCF drying of sorghum. The maximum difference represents the loss of approximately 1.0 gram of starch which is within experimental wet milling errors of 5%.

A protein analysis of the starch without the top (2mm) protein rich layer was made to look for a difference between (in) and (out) starch samples (see Table 8.1.4); no significant difference was established.

Based on the results, it appears that the wet milling quality of sorghum was unaffected by CCF drying, and the and the losses were due to wet milling procedure. In order to verify this conclusion, more CCF drying tests of sorghum are required for a complete statistical analysis. Also, larger CCF dried sorghum samples should be wet milled to minimize wet milling experimental losses; and additional quality tests should be conducted on CCF dried sorghum [such as viscosity (Brabender curves) (Otterbacher and Kite, 1963)].

8.1.5 SUMMARY

Sorghum was dried with DATs as high as 216.7°C (422°F). The maximum transient grain temperature recorded was 96.0°C (205°F) [Thermocouple #13, Test #3, Table 8.1.1a]. Results show that:

(1) germination is reduced to approximately one-half of initial, and

(2) the wet milling characteristics of CCF dried sorghum show no significant change in the starch yield and the protein in the starch after drying.

Sorensen et al. (1949) reported similar findings. More tests are needed with the CC/CF dryer to statistically verify these findings.

8.2 SIMULATION

This section compares experimental and simulation results for the CC/CF dryer. A study of the MSU CC/CF dryer simulation model of Bakker-Arkema et al. (1983a) is also made.

8.2.1 EXPERIMENTAL VERSUS SIMULATION

Table 8.2.1a shows the maximum grain temperatures measured by experiment to be higher than for simulation (especially in the first stage). The experimental temperatures measured at thermocouple 13 were found to be representative of the drying air temperature. Table 8.2.1b shows that predicted grain temperature using simulation is closer to the calculated grain temperature. In test 3 stage 1, the predicted grain temperature is 59.3°C. Simulation at 7.5 cm depth into the drying bed predicts the DAT to be less than 1°C higher than the grain temperature. Using this knowledge and an energy balance

(LHE=AE) the calculated grain temperature is 50.8°C. The measured (Exp) value is 78.2°C. Assuming this value to be the air temperature, the calculated grain temperature is 41.3°C. Thus the experimental grain temperature measurements at thermocouple 13 are really a mixture of grain temperature and DAT combined.

TABLE 8.2.1a

MAXIMUM SORGHUM TEMPERATURES IN THE CCF DRYING BED

TEST	EXPERIMENTAL(°C)[1]	SIMULATION°C
#3 Stage 1	81.6	68.9
2	96.0	86.4
3	93.3	93.9
#5 Stage 1	90.0	65.8
2	79.4	71.8
3	63.3	62.5
#6 Stage 1	85.6	72.4
2	79.4	75.8

[1] Thermocouple #13 (Table 8.1.1a)

TABLE 8.2.1b

VERIFICATION OF PREDICTED AND MEASURED GRAIN TEMPERATURES

(1) An energy balance is used to calculate the average grain temperature at thermocouple #13 and to verify predicted versus experimental grain temperatures (C).

TEST	STAGE	SIM PREDICTED	EXP MEASURED	SIM CALCULATED	EXPERIMENTAL CALCULATED
3	1	59.3	78.2	50.8	41.3
5	1	56.7	86.3	52.8	34.6
6	1	64.3	83.8	49.6	43.6

(1) DATS were assumed to be close to the grain temperatures predicted and measured. An energy blance (LHE=AE) was used to calculate the grain temperature.

Table 8.2.1c compares the M.C.s, grain temperatures and fuel efficiencies for the experimental and simulation tests. Two thin-layer drying equations were used for simulation [Paulsen and Thompson (1973) and Suarez et al. (1980)]. The thin-layer drying equation by Paulsen and Thompson (1973) underpredicts the moisture removal and results in a higher predicted than measured energy consumption. This equation had to be extrapolated beyond the recommended range [up to a DAT of 115°C (240°F)] (see section 6.3). Unfortunately this equation is unstable in the computer program and blows up without warning on occasion.

The Suarez et al. (1980) drying equation slightly overpredicts the moisture removal when compared to the experimental values (Table 8.2.1b; Test #3: M.C. = 9.0% versus 9.4%). Test # 5 shows the largest difference between the predicted and measured M.C. values [10.5% (SIM) versus 11.3% (EXP)]. The difference between simulated and experimental fuel efficiencies is less than 10%. The CC/CF drying simulation model assumes adiabatic conditions, and thus the experimental values are expected to be higher.

The predicted grain temperatures in the drying stages of the three tests are close to the experimental values (Table 8.2.1b). However, the cooling simulation model overpredicts the cooling effect (see Test #3: 8.7°C versus 39.4°C).

It is concluded that:

(1) the CCF drying model (using the Suarez et al. (1980)

TABLE 8.2.1c

SIMULATED VS EXPERIMENTAL RESULTS FOR CC/CF DRIED SORGHUM

TEST NUMBER	TEST 3			TEST 5			TEST 6		
PARAMETER	SIM P + T EQ	SIM SUAREZ EQ	EXP	SIM P + T EQ	SIM SUAREZ EQ	EXP	SIM P + T EQ	SIM SUAREZ EQ	EXP
Inlet M.C. (% w.b.)	15.9	15.9	15.9	15.8	15.8	15.8	15.9	15.9	15.9
Grain Temp (^{o}C)	13.3	13.3	13.3	12.2	12.2	12.2	13.3	13.3	13.3
State I Out									
MC%	14.3	13.9	14.2	14.2	13.8	13.8	14.4	14.2	14.2
Grain Temp (^{o}C)	48.6	44.1	46.1	47.1	42.0	46.1	51.6	47.7	51.7
Stage II Out									
MC%	12.1	11.4	11.0	12.6	11.9	12.3	13.0	12.5	----
Grain Temp (^{o}C)	58.1	54.2	51.7	49.8	46.1	48.9	53.7	50.3	----
Stage III Out									
MC%	10.4	9.1	---	11.7	10.7	---			----
Grain Temp (^{o}C)	63.7	60.9	---	45.4	41.7	---			----
Cooler Out									
MC%	9.8	9.0	9.4	11.6	10.5	11.3	12.8	12.1	12.6
Grain Temp (^{o}C)	8.7	8.6	39.4	5.2	4.8	28.9	21.3	11.3	35.0
Fuel Consumption (KJ/Kg)	5312	4704	4922	6514	5253	5767	5374	4461	4928

(1) P + T EQ_: (Paulsen & Thompson, 1973) thin-layer drying equation
(2) Suarez EQ: (Suarez et al., 1980) thin layer drying equation
(3) Simulation based on experimental parameters measured

diffusion coefficients for thin-layer drying) adequately predicts sorghum drying, (M.C., grain temperatures and fuel efficiencies);

(2) more experimental CCF sorghum drying tests are needed to determine the suitability of the Suarez thin-layer drying equation; and

(3) the Paulsen and Thompson (1973) adequately predicts grain temperature and moisture content.

8.2.2 SIMULATION TESTS

Table 8.2.2a presents the simulation data [using a DAT of 216.7°C (422°F)] of grain temperature verse DAT in a CCF drying bed. The grain temperature and the DAT are only 0.5°C apart after 0.9 minutes at a 6.1 cm depth. A grain temperature above 60°C is often considered very detrimental for germination of sorghum. The grain temperature is only above 60°C (140°F) for approximately 4.5 minutes. This explains why germination is lowered but not completely destroyed in the experimental data.

Table 8.2.2b lists the simulated data for a two and three stage CC/CF dryer. The main conclusions to be drawn from the data are:

(1) the energy efficiency is dependent on the final moisture content, the number of points of moisture removed, the grainflow rate/DAT relationship, the drying air temperature, and the number of drying stages;

TABLE 8.2.2a

SORGHUM AND AIR TEMPERATURE HISTORY IN A CCF DRYING BED (SIMULATION)[3]

DEPTH (m)	TIME (min)	AIR TEMP[1] (°C)	GRAIN TEMP (°C)[2]
0.00	0.0	216.7	13.3
0.061	0.9	74.4	73.9
0.123	1.8	67.2	67.2
0.187	2.7	63.1	62.9
0.244	3.5	60.3	60.2
0.305	4.4	58.2	58.1
0.368	5.3	56.5	56.4
0.427	6.1	55.3	55.2
0.495	7.1	54.2	54.2
0.550	7.9	53.5	53.4
0.611	8.8	52.9	52.8
0.673	9.7	52.3	52.3
0.732	10.5	51.9	51.9

[1] DAT of 216.7°C

[2] Maximum grain temperature predicted 83.3°C

[3] M.C. = 15.9% w.b., SP = 3.277KPa (13.17"), grainflow rate = 311.0 Kg/hr/m^2 (11.0 bushels/hr/ft^2) dry weight

TABLE 8.2.2b

SIMULATED TWO AND THREE-STAGE CC/CF DRYER RUNS FOR SORGHUM

PARAMETERS	THREE STAGE DRYING WITH COOLING										TWO STAGE DRYING WITH COOLING	
	Run #											
		1	2	3	4	5	6	7	8	9	10	11	12
MC in (% w.b.)		15	15	15	18	18	18	22	15	15	15	18	18
MC out (% w.b.)		11	11	11	11	11	11	11	8	8	8	11	11
DAT °C)		232	177	121	232	171	121	232	232	177	121	232	177
Grain Temp Outlet (°C) STAGE	1	47	43	39	48	44	39	48	52	48	43	52	47
	2	59	53	46	58	53	46	57	66	59	52	64	58
	3	66	58	51	66	60	51	66	74	68	59		
Max. grain temp in dryer (°C) STAGE	1	59	56	52	72	69	61	83	76	72	65	87	79
	2	81	73	64	92	85	71	102	98	90	77	108	96
	3	91	81	69	101	92	76	111	109	98	83		
Grainflow rate (dry $Kg/hr/m^2$)		7280	5660	3680	4700	3300	2220	3120	4620	3300	2010	3200	2410
EFFIC (KJ/KgH_2O)		4350	3890	4120	3550	3780	3660	3250	3870	4020	4300	3440	3510

SP = 3484 Pa (14")
SP = 2240 Pa (9.0") cooler
AMB. Temp = 21.1°C (70°F)
DRYING BED = 0.762 m(2.5 ft)
COOLING BED = 1.524m (5.0ft)
Rh = 50%
INITIAL GRAIN TEMP = 21.1°C (70°F)

(2) three-stage CC/CF dryers have a larger capacity and slightly better maximum grain temperature control;

(3) outlet grain temperature is dependent on final moisture content grainflow rate and DAT when a set number of points of moisture must be removed; and

(4) a three-stage CC/CF dryer can reduce the moisture content from 22% to 11% in one pass (Run #7) with an outlet grain temperature of 66°C (151°F) and a maximum transient grain temperature of 111°C (232°F) [approximately 2.2 minutes above 82.2°C (180°F), 7.9 minutes above 71.1°C (160°F) and 17.5 minutes above 60.0°C (140°F)] operating at 232°C (450°F).

In summary, grain temperature history shows the CC/CF dryer is more gentle with respect to drying treatment (at much higher DATs) than conventional dryers of crossflow design. Simulation (Table 8.2.2a) reveals that even Run #7 would produce sorghum with excellent wet milling characteristics.

The drying conditions of the crossflow batch dryer reported by Sorensen et al. (1949) resulted in grain temperatures far more extreme than encountered in the CC/CF dryer in Run #7 (see Table 4.3.1.3a: Batch No. 51 and 52). Sorensen et al. (1949) used a DAT of 110°C (230°F) for 30 minutes without impairing wet milling quality; in Batch No. 50 after drying for 2.57 hours, only a 2% decrease in starch yield occurred with no change in protein content of the starch.

8.2.3 COMMERCIAL DRYER DESIGN

The CC/CF sorghum dryer simulation model was used to design a commercial three-stage CCF dryer for the drying of food sorghum in the Sudan. The contract called for the drying of 280 tons of 25% (w.b.) moisture content sorghum (containing no more than 3% broken kernels and foreign material) to 10% M.C. within a 16 hour period. It was further specified that the sorghum temperature should not exceed 55°C (131°F) to ensure that the drying operation does not change the normal starch recovery. The dryer will operate at a sorghum starch and glucose production company and be heated with 160 psia steam. The limited pressure restricts the maximum drying air temperature to the 162.8 - 176.7°C (325 - 350°F) range.

The design data for a two pass three-stage CC/CF dryer is presented in Table 8.2.3a. The dryer must dry 35 metric ton/hr in order to meet the 280 metric ton limit in 16 hours. At a dry grainflow rate or 2662 Kg/hr/m^2 the simulation dryer is able to dry 35.6 metric ton per two hour period (39.2 wet metric tons per two hours). The final moisture content is 10.0% w.b.

TABLE 8.2.3

DESIGN CONDITIONS FOR A 35-TON/HR THREE-STAGE
3.66m x 3.66m (12' x 12')
CONCURRENTFLOW SORGHUM DRYER

DRYING PARAMETERS	DRYER PASS 1	DRYER PASS 2
Initial grain MC (% w.b.)	25.0	17.7
Initial grain temp (°C)	26.7	45.6
Ambient temp (°C)	26.7	26.7
Ambient RH (%)	20	20
Grainflow rate dry (Kg/hr/m^2)	2662	2662
FIRST STAGE		
Inlet air temp (°C)	176.7	176.7
Airflow rate (m^3/min/m^2)	33.5	33.5
Outlet grain M.C. (% w.b.)	22.95	14.9
Outlet grain temp (°C)	40.0	50.9
SECOND STAGE		
Inlet air temp (°C)	176.7	162.8
Airflow rate (m^3/min/m^2)	27.4	27.4
Outlet grain M.C. (°C)	20.5	12.4
Outlet grain temp (°C)	45.0	54.4
THIRD STAGE		
Inlet air temp (°C)	176.7	126.7
Airflow rate (m^3/min/m^2)	24.4	24.4
Outlet grain M.C. (% w.b.)	17.7	10.6
Outlet grain temp (°C)	47.5	54.5
COOLING STAGE		
Inlet air temp (°C)	----	26.7
Airflow rate (m^3/min/m^2	----	15.2
Final grain M.C. (% w.b.)	----	10.0
Outlet grain temp (°C)	----	30.1
Fuel consumption (KJ/Kg)		3159

The grain outlet temperature reaches a maximum of 54.5°C. The maximum grain temperature in the dryer is 87.2°C. The total time of grain temperature above 60°C(140°F) is 19.7 minutes and above 71.1°C (160°F) is 5.9 minutes.

The fuel efficiency is 3159 KJ/Kg H_2O. It is considerably improved: (1) by drying at high DATs (176.7°C), and (2) by drying at a high initial moisture content (25% down to a low moisture content (10%).

CHAPTER 9

CONCLUSIONS

This study has been concerned with determining the performance of a concurrentflow dryer, and the resulting wet milling quality of the dried sorghum. The experimental data was used to validate a CC/CF sorghum dryer model. The purpose of the simulation model was to design a CC/CF sorghum dryer to be used in the drying of sorghum for starch and glucose production.

The wet milling properties of sorghum are less susceptible to drying damage than corn. A decrease in germination does not necessarily indicate a decrease in wet milling quality of sorghum.

The grain temperature history determines grain damage not the inlet drying air temperature. Therefore, the recommended DATs for wet milling should reflect dryer design. The CC/CF dryer dries sorghum more gently than conventional crossflow dryers although using higher inlet air temperatures.

The following are the main conclusions of this study:

(1) High drying air temperatures (DATs) were found to be more fuel efficient than low DATs and fuel consumption was

found to increase when drying below 10 - 11% MC.

(2) Sorghum wet milling was unaffected by CCF drying (16% to 11% M.C.) at DATs as high as 217°C.

(3) The MSU simulation model for CCF drying of sorghum was verified by experimental data.

(4) A commercial three-stage CCF dryer was designed for a sorghum wet milling factory in the country of the Sudan.

CHAPTER 10

SUGGESTIONS FOR FUTURE STUDY

A more cohesive study of the CC/CF dryer performance and wet milling quality of CC/CF dried sorghum is needed to statistically verify the results in this thesis. Specifically:

(1) Sorghum should be dried at higher initial moisture (25%) contents to final moisture contents of 10 - 11% M.C. and to 7 - 9% M.C.in order to study fuel efficiency and wet milling quality.

(2) Large samples (1 Kg) should be wet milled to minimize washing losses and to determine more accurate yields.

(3) The Suarez equation should be further studied and modified if necessary to eliminate a slight tendency for overdrying.

The three-stage CCF sorghum dryer in the Sudan becomes operational in 1985/1986. This offers an opportunity to run experimental drying tests on local varieties of sorghum. The operational differences between large and small dryers could be compared. The MSU simulation CCF model would be verified by a larger dryer. Samples of CCF dried sorghum could be wet milled to determine starch quality.

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APPENDIX A

Table A Conversion factors

QUANTITY	UNITS	MULTIPLY BY	TO GET
Airflow rate	m3/min/m2	2.8352	ft3/min/bu
Airflow rate	m3/min/m2	3.2808	ft3/min/ft2
Airflow rate	m3/min/ton	0.9291	ft3/min/bu[1]
Area	m2	10.7639	ft2
Convective heat transfer coefficient	kJ/hr/m2/C	0.0489	BTU/hr/ft2/F
Density	kg/m3	0.0624	lb/ft3
Diffusion coefficient	m2/hr	10.7639	ft2/hr
Energy efficiency	kJ/kg	0.4299	BTU/lb
Grainflow rate	kg/hr/m2	0.2048	lb/hr/ft2
Latent heat of vaporization	kJ/kg	0.4299	BTU/lb
Length	m	3.2808	ft
Mass	kg	2.2046	lb
	metric ton	2,204.6	lb
Power	kW	1.3410	HP
Specific Heat	kJ/kg/C	0.2388	BTU/lb/F
Specific surface area	m2/m3	0.3048	ft2/ft3
Static pressure	kPa	4.0186	in. H2O
Temperature difference	C	1.8	F
Thermal conductivity	W/m/C	0.5778	BTU/hr/ft/F
Thermal diffusivity	m2/hr	10.7639	ft2/hr
Velocity	m/hr	3.2808	ft/hr
Volume	m3	35.3147	ft3

[1] A bushel weighs 58 pounds.

APPENDIX B

Table B CC/CF Sorghum Simulation Runs

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT      F=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   1.000

 HOW MANY STAGES #                                          1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                  5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                        40.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                    15.9000
    GRAIN TEMPERATURE, F:                                         56.0000



SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/24/85
 PAULSEN   DRYINGRATE  EQUATION FOR THINLAYER   MILO
          TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                 1
    INLET AIR TEMP, F:                                           325.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                  .0085
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:               95.3000
    GRAIN FLOW RATE, BU@D/H/FT2:                                   7.7000
    DRYER LENGTH, FT:                                              2.4000
    OUTPUT INTERVAL, FT:                                            .5000
    TEMPERING LENGTH, FT:                                         17.0000
CP=  .3551E+00 BTU/LB/F  HFG=  .1088E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0020
AIR FLOW RATE    421.9LB/HR/FT2,  95.3CFM/FT2  , 144.9CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9873E+04 ; BTU/HRFT2F  .3056E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   3.49687  DRY BASIS,DECIMAL  .0362358
INLET MOISTURE, DRY BASIS DECIMAL .1891
GRAIN VELOCITY FT/HR  9.58 LB/HR/FT2  461.59
[WET-BU@D/H/FT2     9.42  WET-MTON/HR/M2     2.68]


  DEPTH    TIME      AIR      ABS      REL    GRAIN      MC       MC
                    TEMP      HUM      HUM    TEMP       WB       EQ
     FT      HR        F   LB/LB DECIMAL         F PERCENT PERCENT
   0.000   0.000   325.0   .0085   .0020     56.0   15.90   .0999
    .504    .053   131.5   .0261   .2491    131.3   14.75  7.5451
   1.008    .105   126.4   .0291   .3166    126.4   14.55  8.4384
   1.501    .157   123.3   .0309   .3650    123.3   14.43  9.0461
   2.010    .210   121.1   .0322   .4050    121.0   14.34  9.5375
   2.400    .251   119.7   .0331   .4309    119.6   14.28  9.8538
    THE MAX. GRAIN TEMP. IS 146.10418 F THIS HAPPENS AT  .2432E-02 HOURS
    THE MAX.TEMPER TEMP. IS 119.64190 F THIS HAPPENS AT 0.         HOURS
                           [WET-FLOW:FT/HR INTO     11.71;FROM    11.39]
STATIC PRESSURE, IN OF H2O       12.54     ;  .3121E+01 KPA
```

```
HORSEPOWER, HP/FT2    .1882 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .7634E+04 ; LB-H20/FT2 =  .2589E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1885.83 BTU/LB-H20 IF AT 50.00 F
ENERGY INPUTS, BTU/LB
         FAN(   .50 EFF)             1.97
              HEAT AIR              64.03
              MOVE GRAIN             0.00
              CUMULATIVE            66.00

WATER REMOVED, LB/LB      .0224

BTU/LB H20  2945.66      ; THIS STAGE BTU/LB H20=   2945.66


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT       F=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   1.000

 HOW MANY STAGES #                                          1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                  5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                       40.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                   14.2800
    GRAIN TEMPERATURE, F:                                       109.4000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/24/85
 PAULSEN   DRYINGRATE  EQUATION FOR THINLAYER   MILO
          TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                 1
    INLET AIR TEMP, F:                                         325.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                .0085
RH (EITHER AMBIENT OR ENTERED) TO HEATER=       .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:              91.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                  7.7000
    DRYER LENGTH, FT:                                             2.4000
    OUTPUT INTERVAL, FT:                                           .5000
    TEMPERING LENGTH, FT:                                        17.0000
CP=  .3409E+00 BTU/LB/F  HFG=  .1071E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1      PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0020
AIR FLOW RATE    402.9LB/HR/FT2,  91.0CFM/FT2  , 138.4CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9577E+04 ; BTU/HRFT2F  .2964E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   2.40519  DRY BASIS,DECIMAL  .0246447
INLET MOISTURE, DRY BASIS DECIMAL .1666
GRAIN VELOCITY FT/HR  9.58 LB/HR/FT2  461.59
[WET-BU@D/H/FT2     9.16  WET-MTON/HR/M2     2.63]
```

DEPTH FT	TIME HR	AIR TEMP F	ABS HUM LB/LB	REL HUM DECIMAL	GRAIN TEMP F	MC WB PERCENT	MC EQ PERCENT
0.000	0.000	325.0	.0085	.0020	109.4	14.28	.0999
.505	.053	149.5	.0347	.2064	149.3	12.57	6.7191
1.019	.106	143.7	.0381	.2605	143.6	12.34	7.5050
1.502	.157	140.5	.0399	.2954	140.4	12.22	7.9762
2.001	.209	138.2	.0413	.3233	138.2	12.13	8.3407
2.400	.251	136.8	.0421	.3418	136.7	12.07	8.5778

```
    THE MAX. GRAIN TEMP. IS 168.12018 F THIS HAPPENS AT  .2826E-02 HOURS
    THE MAX.TEMPER TEMP. IS 136.73161 F THIS HAPPENS AT 0.         HOURS
                             [WET-FLOW:FT/HR INTO     11.39;FROM    10.97]
STATIC PRESSURE, IN OF H2O        12.48      ;  .3106E+01 KPA
```

```
HORSEPOWER, HP/FT2   .1788 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .7288E+04 ; LB-H20/FT2 =  .3385E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1196.04 BTU/LB-H20 IF AT 50.00 F
ENERGY INPUTS, BTU/LB
         FAN(   .50 EFF)              1.87
              HEAT AIR               61.14
              MOVE GRAIN              0.00
              CUMULATIVE             63.01

WATER REMOVED, LB/LB     .0293

BTU/LB H20  2150.62     ; THIS STAGE BTU/LB H20=   2150.62


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT      F=DTE
[SHOW T;CKDT F:  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   2.000

 HOW MANY STAGES #                                          2
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                  5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                     40.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                 12.0700
    GRAIN TEMPERATURE, F:                                     117.2000



SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/24/85
 PAULSEN   DRYINGRATE  EQUATION FOR THINLAYER   MILO
NODE= 0 10 FLUX -.3857E+07  .3857E+07 10 GRID 0.          .8819E-03 V=  0.0000
NODE= 1 10 FLUX 0.          .1570E+08 10 GRID  .8819E-03  .1111E-02 V=   .2500
NODE= 2 10 FLUX  .1118E+08  .4783E+08 10 GRID  .1111E-02  .1272E-02 V=   .2500
NODE= 3 10 FLUX  .2871E+08  .7212E+08 10 GRID  .1272E-02  .1400E-02 V=   .2500
NODE= 4 10 FLUX  .4962E+08  .9794E+08 10 GRID  .1400E-02  .1508E-02 V=   .2500
THICKNESS OF ME LAYER=  .1081E-03
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                 1
    INLET AIR TEMP, F:                                       325.0000
    INLET ABSOLUTE HUMIDITY RATIO:                             .0085
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:           90.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                               7.7000
    DRYER LENGTH, FT:                                          2.4000
    OUTPUT INTERVAL, FT:                                        .5000
    TEMPERING LENGTH, FT:                                      0.0000

STAGE 2 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                 5
    INLET AIR TEMP, F:                                        40.0000
    INLET ABSOLUTE HUMIDITY RATIO:                             .0032
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:          120.0000
STATIC PRESSURE BOUND     7.0000 IN    H2O     AIRFLOW BOUND   150.0000 CFM/FT2
    GRAIN FLOW RATE, BU@D/H/FT2:                               7.7000
    DRYER LENGTH, FT:                                          1.0000
    OUTPUT INTERVAL, FT:                                        .5000
    TEMPERING LENGTH, FT:                                      0.0000
GUESSED AIRFLOW=  .1200E+03 CFM/FT2   CORRECTED=  .1351E+03 CFM/FT2
ASSUMING AIRFLOW IN GRAIN BED AT  150.0F IS  135.1CFM/FT2
NODE= 0 10 FLUX -.3857E+07  .3857E+07 10 GRID 0.          .8819E-03 V=  0.0000
NODE= 1 10 FLUX 0.          .1570E+08 10 GRID  .8819E-03  .1111E-02 V=   .2500
NODE= 2 10 FLUX  .1118E+08  .4783E+08 10 GRID  .1111E-02  .1272E-02 V=   .2500
NODE= 3 10 FLUX  .2871E+08  .7212E+08 10 GRID  .1272E-02  .1400E-02 V=   .2500
NODE= 4 10 FLUX  .4962E+08  .9794E+08 10 GRID  .1400E-02  .1508E-02 V=   .2500
THICKNESS OF ME LAYER=  .1081E-03
```

```
CP=  .3225E+00 BTU/LB/F  HFG=  .1097E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0020
AIR FLOW RATE     398.5LB/HR/FT2,  90.0CFM/FT2  , 136.9CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9507E+04 ; BTU/HRFT2F  .2943E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   2.26284  DRY BASIS,DECIMAL  .0231523
INLET MOISTURE, DRY BASIS DECIMAL .1373
GRAIN VELOCITY FT/HR  9.58 LB/HR/FT2  461.59
[WET-BU@D/H/FT2     8.82  WET-MTON/HR/M2     2.56]


  DEPTH    TIME      AIR      ABS      REL   GRAIN       MC       MC
                    TEMP      HUM      HUM    TEMP       WB       EQ
     FT      HR        F    LB/LB DECIMAL        F PERCENT PERCENT
   0.000   0.000   325.0   .0085   .0020   117.2   12.07   .0999
METHOD 3 STEPS [MIN CURRENT MAX X]  .1000E-05  .1000E-03  .5000E-01  .4000E-03
METHOD 3 STEPS [MIN CURRENT MAX X]  .1000E-05  .1600E-02  .5000E-01  .1532E+00
    .503    .052   159.3   .0317   .1486   159.2   10.50  5.7271
METHOD 3 STEPS [MIN CURRENT MAX X]  .1000E-05  .1600E-02  .5000E-01  .3052E+00
   1.001    .105   153.6   .0348   .1866   153.5   10.28  6.3813
METHOD 3 STEPS [MIN CURRENT MAX X]  .1000E-05  .3200E-02  .5000E-01  .4620E+00
   1.516    .158   150.2   .0367   .2131   150.2   10.15  6.7969
METHOD 3 STEPS [MIN CURRENT MAX X]  .1000E-05  .3200E-02  .5000E-01  .6108E+00
   2.004    .209   148.0   .0379   .2322   148.0   10.07  7.0806
METHOD 3 STEPS [MIN CURRENT MAX X]  .1000E-05  .2344E-02  .5000E-01  .7315E+00
   2.400    .251   146.6   .0386   .2449   146.6   10.02  7.2642
    THE MAX. GRAIN TEMP. IS 176.51786 F THIS HAPPENS AT  .2826E-02 HOURS
                            [WET-FLOW:FT/HR INTO    10.97;FROM    10.60]
STATIC PRESSURE, IN OF H20       12.48      ;  .3106E+01 KPA
HORSEPOWER, HP/FT2   .1769 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .7208E+04 ; LB-H20/FT2 =  .3001E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1260.99 BTU/LB-H20 IF AT 50.00 F
ENERGY INPUTS, BTU/LB
        FAN(   .50 EFF)              1.85
             HEAT AIR               60.47
             MOVE GRAIN              0.00
             CUMULATIVE             62.32

WATER REMOVED, LB/LB      .0260

BTU/LB H20  2399.62      ; THIS STAGE BTU/LB H20=   2399.62


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE   0.00
CP=  .3061E+00 BTU/LB/F  HFG=  .1124E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   2     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .6000
AIR FLOW RATE     510.5LB/HR/FT2, 115.3CFM/FT2  , 110.7CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .1120E+05 ; BTU/HRFT2F  .3465E+02
EQUILIBRIUM MOISTURE, WB PERCENT=  11.91217  DRY BASIS,DECIMAL  .1352306
INLET MOISTURE, DRY BASIS DECIMAL .1113
GRAIN VELOCITY FT/HR  9.58 LB/HR/FT2  461.59
[WET-BU@D/H/FT2     8.52  WET-MTON/HR/M2     2.50]
IFLOW=2 RICATTI, IFLOW=3 ASAE83D  3
SHOW GPGA RGPGA
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 .5817E+02  .6069E+02  .6378E+02  .6711E+02  .7346E+02
CKDT SQ2
 .4444E+01  .1365E+02  .2135E+02  .2628E+02  .2976E+02
 .3234E+02  .3421E+02  .3557E+02  .3670E+02  .3785E+02
 .3894E+02  .3991E+02  .4088E+02  .4166E+02  .4263E+02
 .4366E+02  .4470E+02  .4578E+02  .4667E+02  .4781E+02
 .4893E+02  .5032E+02  .5191E+02  .5354E+02  .5540E+02
 .5749E+02  .5991E+02  .6278E+02  .6588E+02  .7175E+02
CKDT THSTG,BACK
 .6367E+02  .7346E+02
CKDT TH OUTLET
 .8724E+01
MAY NOT HAVE CONVERGED, REQUIRED ALL   4 PASSES


  DEPTH    TIME     AIR     ABS     REL   GRAIN     MC      MC
                    TEMP    HUM     HUM   TEMP      WB      EQ
     FT      HR       F   LB/LB DECIMAL       F PERCENT PERCENT
   0.000   0.000   161.1   .0054   .0255   146.6   10.02  2.8628
    .500    .052   109.7   .0035   .0640   110.2    9.84  4.8325
   1.000    .104    40.0   .0032   .6000    47.7    9.83 13.0720
                          [WET-FLOW:FT/HR INTO    10.60;FROM    10.57]
STATIC PRESSURE, IN OF H20         7.01      ;  .1744E+01 KPA
HORSEPOWER, HP/FT2   .1273 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .6412E+02 ; LB-H20/FT2 =  .1092E+00
CUMULATIVE STANDARD SPECIFIC ENERGY   2278.78 BTU/LB-H20 IF AT 50.00 F
ENERGY INPUTS, BTU/LB
        FAN(  .50 EFF)               1.33
             HEAT AIR                0.00
             MOVE GRAIN              0.00
             CUMULATIVE             63.65

WATER REMOVED, LB/LB      .0282

BTU/LB H20  2254.00      ; THIS STAGE BTU/LB H20=    586.57


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT      T=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   1.000

 HOW MANY STAGES #                                         1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                  5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                      40.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                  15.9000
    GRAIN TEMPERATURE, F:                                       56.0000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 SUAREZ    DIFFUSION   EQUATION FOR SPHERICAL   MILO
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                 1
    INLET AIR TEMP, F:                                         325.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                .0085
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:             95.3000
    GRAIN FLOW RATE, BU@D/H/FT2:                                 7.7000
    DRYER LENGTH, FT:                                            2.4000
    OUTPUT INTERVAL, FT:                                          .5000
    TEMPERING LENGTH, FT:                                       17.0000
CP=  .3551E+00 BTU/LB/F  HFG=  .1088E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0020
AIR FLOW RATE     421.9LB/HR/FT2,  95.3CFM/FT2  , 144.9CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9873E+04 ; BTU/HRFT2F  .3056E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   3.49687  DRY BASIS,DECIMAL  .0362358
INLET MOISTURE, DRY BASIS DECIMAL .1891
GRAIN VELOCITY FT/HR  9.58 LB/HR/FT2  461.59
[WET-BU@D/H/FT2     9.42  WET-MTON/HR/M2     2.68]


  DEPTH    TIME     AIR     ABS     REL   GRAIN     MC      MC
                    TEMP    HUM     HUM   TEMP      WB      EQ
    FT      HR       F    LB/LB DECIMAL      F PERCENT PERCENT
  0.000   0.000   325.0   .0085   .0020    56.0   15.90    .0999
   .502    .052   128.4   .0280   .2902   128.0   14.62  8.1003
  1.002    .105   118.6   .0338   .4537   118.4   14.24 10.1327
  1.509    .157   114.3   .0363   .5476   114.2   14.07 11.3004
  2.002    .209   112.2   .0374   .5984   112.2   13.99 11.9654
  2.400    .251   111.3   .0380   .6235   111.3   13.95 12.3077
INTERNAL MOISTURE AFTER DRYING FOR  .2506E+00 HR
    .1571      .1454      .1299      .1210
    THE MAX. GRAIN TEMP. IS 155.71735 F THIS HAPPENS AT  .3220E-02 HOURS
INTERNAL MOISTURE AFTER TEMPERING FOR  .1846E+01 HR
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    .1398      .1383      .1380      .1381
   THE MAX.TEMPER TEMP. IS 111.26497 F THIS HAPPENS AT O.        HOURS
                           [WET-FLOW:FT/HR INTO    11.71:FROM    11.33]
STATIC PRESSURE, IN OF H20        12.45     ;  .3098E+01 KPA
HORSEPOWER, HP/FT2   .1868 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .7632E+04 ; LB-H20/FT2 =  .3112E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1680.90 BTU/LB-H20 IF AT 50.00 F
ENERGY INPUTS, BTU/LB
         FAN(   .50 EFF)                1.95
              HEAT AIR                 64.03
              MOVE GRAIN                0.00
              CUMULATIVE               65.99

WATER REMOVED, LB/LB     .0269

BTU/LB H20  2450.07     ; THIS STAGE BTU/LB H20=   2450.07


QUALITY CHANGE, PERCENT     -1     TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT      T=OTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   1.000

 HOW MANY STAGES #                                         1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                 5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                        40.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                    13.9500
    GRAIN TEMPERATURE, F:                                        109.4000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 SUAREZ    DIFFUSION   EQUATION FOR SPHERICAL   MILO
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                1
    INLET AIR TEMP, F:                                           325.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                  .0085
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:               91.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                   7.7000
    DRYER LENGTH, FT:                                              2.4000
    OUTPUT INTERVAL, FT:                                            .5000
    TEMPERING LENGTH, FT:                                         17.0000
CP=  .3381E+00 BTU/LB/F  HFG=  .1074E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0020
AIR FLOW RATE    402.9LB/HR/FT2,  91.0CFM/FT2  , 138.4CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9577E+04 ; BTU/HRFT2F  .2964E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   2.40519  DRY BASIS,DECIMAL  .0246447
INLET MOISTURE, DRY BASIS DECIMAL .1621
GRAIN VELOCITY FT/HR  9.58 LB/HR/FT2  461.59
[WET-BU@D/H/FT2     9.10  WET-MTON/HR/M2     2.62]
```

DEPTH FT	TIME HR	AIR TEMP F	ABS HUM LB/LB	REL HUM DECIMAL	GRAIN TEMP F	MC WB PERCENT	MC EQ PERCENT
0.000	0.000	325.0	.0085	.0020	109.4	13.95	.0999
.501	.052	150.0	.0346	.2033	149.6	12.23	6.6721
1.001	.105	138.7	.0410	.3172	138.6	11.80	8.2627
1.505	.157	133.6	.0439	.3861	133.6	11.60	9.1336
2.001	.209	131.0	.0455	.4277	130.9	11.50	9.6486
2.400	.251	129.6	.0462	.4501	129.6	11.44	9.9258

```
INTERNAL MOISTURE AFTER DRYING FOR  .2506E+00 HR
   .1343       .1169       .1036       .0981
    THE MAX. GRAIN TEMP. IS 186.42232 F THIS HAPPENS AT  .2740E-02 HOURS
INTERNAL MOISTURE AFTER TEMPERING FOR  .1846E+01 HR
```

```
     .1138      .1134      .1133      .1133
    THE MAX.TEMPER TEMP. IS 129.60284 F THIS HAPPENS AT 0.        HOURS
                          [WET-FLOW:FT/HR INTO    11.33;FROM    10.86]
STATIC PRESSURE, IN OF H20        12.43     ;  .3094E+01 KPA
HORSEPOWER, HP/FT2   .1782 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .7288E+04 ; LB-H20/FT2 =  .3800E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1147.63 BTU/LB-H20 IF AT 50.00 F
ENERGY INPUTS, BTU/LB
         FAN(   .50 EFF)              1.86
              HEAT AIR               61.14
              MOVE GRAIN              0.00
              CUMULATIVE             63.01

WATER REMOVED, LB/LB      .0329

BTU/LB H20  1915.94     ; THIS STAGE BTU/LB H20=   1915.94


QUALITY CHANGE, PERCENT     -1     TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNITS 2      1=ECHO
DEFAULT      T=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   2.000

 HOW MANY STAGES #                                               2
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                       5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                          40.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                      11.4400
    GRAIN TEMPERATURE, F:                                          118.4000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/24/85
 SUAREZ    DIFFUSION   EQUATION FOR SPHERICAL   MILO
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                      1
    INLET AIR TEMP, F:                                             325.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                    .0085
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:                 90.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                     7.7000
    DRYER LENGTH, FT:                                                2.4000
    OUTPUT INTERVAL, FT:                                              .5000
    TEMPERING LENGTH, FT:                                            0.0000

STAGE 2 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                      5
    INLET AIR TEMP, F:                                              40.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                    .0032
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:                 99.0000
STATIC PRESSURE BOUND     7.0000 IN    H20     AIRFLOW BOUND   150.0000 CFM/FT2
    GRAIN FLOW RATE, BU@D/H/FT2:                                     7.7000
    DRYER LENGTH, FT:                                                1.0000
    OUTPUT INTERVAL, FT:                                              .5000
    TEMPERING LENGTH, FT:                                            0.0000
GUESSED AIRFLOW=  .9900E+02 CFM/FT2   CORRECTED=  .1349E+03 CFM/FT2
ASSUMING AIRFLOW IN GRAIN BED AT  150.0F IS  134.9CFM/FT2
CP=  .3174E+00 BTU/LB/F  HFG=  .1108E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0020
AIR FLOW RATE     398.5LB/HR/FT2,  90.0CFM/FT2  , 136.9CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9507E+04 ; BTU/HRFT2F  .2943E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   2.24127  DRY BASIS,DECIMAL  .0229266
INLET MOISTURE, DRY BASIS DECIMAL .1292
GRAIN VELOCITY FT/HR  9.58 LB/HR/FT2  461.59
[WET-BU@D/H/FT2     8.73  WET-MTON/HR/M2     2.54]
```

DEPTH	TIME	AIR	ABS	REL	GRAIN	MC	MC
		TEMP	HUM	HUM	TEMP	WB	EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	325.0	.0085	.0020	118.4	11.44	.0999
.502	.052	160.7	.0314	.1428	160.4	9.86	5.6162
1.011	.106	150.3	.0369	.2144	150.2	9.47	6.8140
1.523	.159	145.5	.0395	.2569	145.5	9.30	7.4320
2.003	.209	143.1	.0408	.2821	143.0	9.20	7.7784
2.400	.251	141.7	.0415	.2966	141.7	9.15	7.9731

INTERNAL MOISTURE AFTER DRYING FOR .2506E+00 HR

.1077 .0918 .0825 .0792

THE MAX. GRAIN TEMP. IS 194.74868 F THIS HAPPENS AT .2706E-02 HOURS

[WET-FLOW:FT/HR INTO 10.86;FROM 10.45]

STATIC PRESSURE, IN OF H2O 12.47 ; .3103E+01 KPA
HORSEPOWER, HP/FT2 .1767 (EFF= 1.00)
ENERGY AND WATER BTU/FT2 = .7208E+04 ; LB-H2O/FT2 = .3285E+01
CUMULATIVE STANDARD SPECIFIC ENERGY 1226.50 BTU/LB-H2O IF AT 50.00 F
ENERGY INPUTS, BTU/LB

FAN(.50 EFF)	1.85
HEAT AIR	60.47
MOVE GRAIN	0.00
CUMULATIVE	62.32

WATER REMOVED, LB/LB .0284

BTU/LB H2O 2192.29 ; THIS STAGE BTU/LB H2O= 2192.29

QUALITY CHANGE, PERCENT -1 TOTAL CHANGE 0.00
CP= .2995E+00 BTU/LB/F HFG= .1154E+04 BTU/LB CA= .2419E+00 BTU/LB/F

OUTPUT FOR STAGE 2 PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .6000
AIR FLOW RATE 509.9LB/HR/FT2, 115.2CFM/FT2 , 110.6CFM/FT2 [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F .1119E+05 ; BTU/HRFT2F .3463E+02
EQUILIBRIUM MOISTURE, WB PERCENT= 11.89465 DRY BASIS,DECIMAL .1350049
INLET MOISTURE, DRY BASIS DECIMAL .1008
GRAIN VELOCITY FT/HR 9.58 LB/HR/FT2 461.59
[WET-BU@D/H/FT2 8.40 WET-MTON/HR/M2 2.48]
IFLOW=2 RICATTI, IFLOW=3 ASAE83D 3

DEPTH	TIME	AIR	ABS	REL	GRAIN	MC	MC
		TEMP	HUM	HUM	TEMP	WB	EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	153.3	.0043	.0244	141.7	9.15	2.8826
.500	.052	87.8	.0032	.1122	87.5	8.92	6.2807
1.000	.104	40.0	.0032	.6000	47.5	8.98	13.0757

INTERNAL MOISTURE AFTER COOLING FOR .1044E+00 HR

.1067 .0908 .0813 .0783

[WET-FLOW:FT/HR INTO 10.45;FROM 10.42]

STATIC PRESSURE, IN OF H2O 7.00 ; .1741E+01 KPA
HORSEPOWER, HP/FT2 .1269 (EFF= 1.00)
ENERGY AND WATER BTU/FT2 = .6393E+02 ; LB-H2O/FT2 = .9958E-01
CUMULATIVE STANDARD SPECIFIC ENERGY 2111.41 BTU/LB-H2O IF AT 50.00 F
ENERGY INPUTS, BTU/LB

FAN(.50 EFF)	1.33

```
              HEAT AIR                 0.00
              MOVE GRAIN               0.00
              CUMULATIVE              63.65

WATER REMOVED, LB/LB      .0305

BTU/LB H20  2087.09     ; THIS STAGE BTU/LB H20=    641.34


QUALITY CHANGE, PERCENT     -1     TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2     1=ECHO
DEFAULT      F=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   1.000

 HOW MANY STAGES #                                             1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                     5
  INPUT IN   ENGLISH UNITS.

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                         30.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                     15.8000
    GRAIN TEMPERATURE, F:                                          54.0000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 PAULSEN   DRYINGRATE  EQUATION FOR THINLAYER   MILO
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                    1
    INLET AIR TEMP, F:                                            295.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                   .0071
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:                93.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                    6.9000
    DRYER LENGTH, FT:                                               2.4000
    OUTPUT INTERVAL, FT:                                             .5000
    TEMPERING LENGTH, FT:                                          17.0000
CP=  .3542E+00 BTU/LB/F  HFG=  .1090E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0026
AIR FLOW RATE     428.6LB/HR/FT2,  93.0CFM/FT2  , 141.2CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9975E+04 ; BTU/HRFT2F  .3087E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   3.54246  DRY BASIS,DECIMAL  .0367256
INLET MOISTURE, DRY BASIS DECIMAL .1876
GRAIN VELOCITY FT/HR  8.58 LB/HR/FT2  413.63
[WET-BU@D/H/FT2      8.42  WET-MTON/HR/M2      2.40]


  DEPTH    TIME      AIR       ABS      REL    GRAIN       MC       MC
                     TEMP      HUM      HUM    TEMP        WB       EQ
    FT      HR        F     LB/LB DECIMAL         F PERCENT PERCENT
   0.000   0.000    295.0    .0071    .0026     54.0    15.80    .0999
    .502    .059    128.9    .0216    .2222    128.8    14.72   7.2399
   1.004    .117    123.8    .0244    .2879    123.7    14.51   8.1391
   1.502    .175    120.6    .0262    .3364    120.5    14.38   8.7599
   2.001    .233    118.2    .0274    .3757    118.2    14.28   9.2473
   2.400    .280    116.7    .0282    .4026    116.7    14.22   9.5758
    THE MAX. GRAIN TEMP. IS 143.66429 F THIS HAPPENS AT  .2599E-02 HOURS
    THE MAX.TEMPER TEMP. IS 116.71026 F THIS HAPPENS AT 0.         HOURS
                           [WET-FLOW:FT/HR INTO     10.48;FROM     10.20]
STATIC PRESSURE, IN OF H20        12.61      ;  .3138E+01 KPA
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HORSEPOWER, HP/FT2   .1847 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .8034E+04 ; LB-H20/FT2 =  .2531E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1979.04 BTU/LB-H20 IF AT 40.00 F
ENERGY INPUTS, BTU/LB
         FAN(   .50 EFF)             2.16
              HEAT AIR              67.31
              MOVE GRAIN             0.00
              CUMULATIVE            69.46

WATER REMOVED, LB/LB      .0219

BTU/LB H20  3171.22     ; THIS STAGE BTU/LB H20=   3171.22


QUALITY CHANGE, PERCENT     -1     TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT      F=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:    1.000

 HOW MANY STAGES #                                            1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                    5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                      30.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                  14.2200
    GRAIN TEMPERATURE, F:                                       97.0000



SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 PAULSEN   DRYINGRATE  EQUATION FOR THINLAYER   MILO
          TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                   1
    INLET AIR TEMP, F:                                         245.0000
    INLET ABSOLUTE HUMIDITY RATIO:                               .0062
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:             92.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                 6.9000
    DRYER LENGTH, FT:                                            2.4000
    OUTPUT INTERVAL, FT:                                          .5000
    TEMPERING LENGTH, FT:                                       17.0000
CP=  .3404E+00 BTU/LB/F  HFG=  .1079E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1      PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0051
AIR FLOW RATE     424.0LB/HR/FT2,  92.0CFM/FT2  , 130.3CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9904E+04 ; BTU/HRFT2F  .3065E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   2.63952  DRY BASIS,DECIMAL  .0271108
INLET MOISTURE, DRY BASIS DECIMAL .1658
GRAIN VELOCITY FT/HR  8.58 LB/HR/FT2  413.63
[WET-BU@D/H/FT2      8.20  WET-MTON/HR/M2      2.35]


  DEPTH    TIME     AIR      ABS      REL    GRAIN      MC       MC
                    TEMP     HUM      HUM    TEMP       WB       EQ
    FT      HR       F     LB/LB DECIMAL       F PERCENT PERCENT
  0.000    0.000   245.0    .0062    .0051    97.0    14.22    .3408
   .504     .059   132.8    .0209    .1947   132.6    13.09   6.8084
  1.008     .117   128.0    .0234    .2468   127.9    12.90   7.5685
  1.501     .175   125.1    .0250    .2840   125.0    12.78   8.0720
  2.000     .233   122.9    .0261    .3142   122.9    12.69   8.4639
  2.400     .280   121.6    .0268    .3348   121.6    12.63   8.7244
    THE MAX. GRAIN TEMP. IS 146.51656 F THIS HAPPENS AT  .2561E-02 HOURS
    THE MAX.TEMPER TEMP. IS 121.55642 F THIS HAPPENS AT 0.         HOURS
                          [WET-FLOW:FT/HR INTO     10.20;FROM     9.92]
STATIC PRESSURE, IN OF H20        12.51      ;  .3113E+01 KPA
```

```
HORSEPOWER, HP/FT2    .1812 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .6482E+04 ; LB-H20/FT2 =  .2447E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1386.83 BTU/LB-H20 IF AT 40.00 F
ENERGY INPUTS, BTU/LB
         FAN(   .50 EFF)              2.11
              HEAT AIR               53.93
              MOVE GRAIN              0.00
              CUMULATIVE             56.04

WATER REMOVED, LB/LB     .0212

BTU/LB H20  2646.69     ; THIS STAGE BTU/LB H20=   2646.69


QUALITY CHANGE, PERCENT     -1     TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT       F=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   2.000

 HOW MANY STAGES #                                            2
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                    5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                      30.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                  12.6300
    GRAIN TEMPERATURE, F:                                       98.6000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 PAULSEN   DRYINGRATE  EQUATION FOR THINLAYER   MILO
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                   1
    INLET AIR TEMP, F:                                         185.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                .0050
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:             94.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                 6.9000
    DRYER LENGTH, FT:                                            2.4000
    OUTPUT INTERVAL, FT:                                          .5000
    TEMPERING LENGTH, FT:                                        0.0000

STAGE 2 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                   5
    INLET AIR TEMP, F:                                          40.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                .0023
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:            120.0000
STATIC PRESSURE BOUND     7.2000 IN   H20     AIRFLOW BOUND   150.0000 CFM/FT2
    GRAIN FLOW RATE, BU@D/H/FT2:                                 6.9000
    DRYER LENGTH, FT:                                            1.0000
    OUTPUT INTERVAL, FT:                                          .5000
    TEMPERING LENGTH, FT:                                        0.0000
GUESSED AIRFLOW=  .1200E+03 CFM/FT2   CORRECTED=  .1375E+03 CFM/FT2
ASSUMING AIRFLOW IN GRAIN BED AT  150.0F IS  137.5CFM/FT2
CP=  .3271E+00 BTU/LB/F  HFG=  .1099E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM. DECIMAL .0137
AIR FLOW RATE    433.2LB/HR/FT2,  94.0CFM/FT2  , 121.5CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .1005E+05 ; BTU/HRFT2F  .3109E+02
EQUILIBRIUM MOISTURE, WB PERCENT=  2.95073  DRY BASIS,DECIMAL  .0304045
INLET MOISTURE, DRY BASIS DECIMAL .1446
GRAIN VELOCITY FT/HR  8.58 LB/HR/FT2  413.63
[WET-BU@D/H/FT2     7.98  WET-MTON/HR/M2     2.31]
```

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	185.0	.0050	.0137	98.6	12.63	1.5132
.502	.059	123.9	.0115	.1380	123.8	12.11	6.0976
1.001	.117	119.7	.0137	.1835	119.6	11.93	6.8581
1.505	.175	116.9	.0150	.2177	116.9	11.82	7.3690
2.009	.234	114.9	.0160	.2453	114.9	11.74	7.7564
2.400	.280	113.7	.0167	.2636	113.7	11.69	8.0038

THE MAX. GRAIN TEMP. IS 134.32886 F THIS HAPPENS AT .2943E-02 HOURS
[WET-FLOW:FT/HR INTO 9.92;FROM 9.77]
STATIC PRESSURE, IN OF H20 12.35 ; .3072E+01 KPA
HORSEPOWER, HP/FT2 .1828 (EFF= 1.00)
ENERGY AND WATER BTU/FT2 = .4832E+04 ; LB-H20/FT2 = .1407E+01
CUMULATIVE STANDARD SPECIFIC ENERGY 1498.19 BTU/LB-H20 IF AT 40.00 F
ENERGY INPUTS, BTU/LB

FAN(.50 EFF)	2.13
HEAT AIR	39.64
MOVE GRAIN	0.00
CUMULATIVE	41.77

WATER REMOVED, LB/LB .0122

BTU/LB H20 3430.54 ; THIS STAGE BTU/LB H20= 3430.54

QUALITY CHANGE, PERCENT -1 TOTAL CHANGE 0.00
CP= .3194E+00 BTU/LB/F HFG= .1106E+04 BTU/LB CA= .2419E+00 BTU/LB/F

OUTPUT FOR STAGE 2 PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .4359
AIR FLOW RATE 520.6LB/HR/FT2, 113.0CFM/FT2 , 112.7CFM/FT2 [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F .1134E+05 ; BTU/HRFT2F .3510E+02
EQUILIBRIUM MOISTURE, WB PERCENT= 10.24155 DRY BASIS,DECIMAL .1141012
INLET MOISTURE, DRY BASIS DECIMAL .1324
GRAIN VELOCITY FT/HR 8.58 LB/HR/FT2 413.63
[WET-BU@D/H/FT2 7.85 WET-MTON/HR/M2 2.29]
IFLOW=2 RICATTI, IFLOW=3 ASAE83D 3

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	118.6	.0031	.0430	113.7	11.69	4.1459
.500	.058	75.3	.0024	.1274	75.9	11.63	6.7693
1.000	.117	40.0	.0023	.4359	41.4	11.61	11.2872

[WET-FLOW:FT/HR INTO 9.77;FROM 9.76]
STATIC PRESSURE, IN OF H20 7.21 ; .1795E+01 KPA
HORSEPOWER, HP/FT2 .1283 (EFF= 1.00)
ENERGY AND WATER BTU/FT2 = .2195E+03 ; LB-H20/FT2 = .4673E-01
CUMULATIVE STANDARD SPECIFIC ENERGY 3489.20 BTU/LB-H20 IF AT 40.00 F
ENERGY INPUTS, BTU/LB

FAN(.50 EFF)	1.50
HEAT AIR	3.06
MOVE GRAIN	0.00
CUMULATIVE	46.33

```
WATER REMOVED, LB/LB      .0131

BTU/LB H20  3523.74      ; THIS STAGE BTU/LB H20=    4693.04


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE    0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNITS 2      1=ECHO
DEFAULT       T=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:    1.000

 HOW MANY STAGES #                                            1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                    5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                        30.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                    15.8000
    GRAIN TEMPERATURE, F:                                         54.0000



SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 SUAREZ    DIFFUSION   EQUATION FOR SPHERICAL   MILO
          TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                   1
    INLET AIR TEMP, F:                                           295.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                  .0071
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:               93.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                   6.9000
    DRYER LENGTH, FT:                                              2.4000
    OUTPUT INTERVAL, FT:                                            .5000
    TEMPERING LENGTH, FT:                                         17.0000
CP=  .3542E+00 BTU/LB/F  HFG=  .1090E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE    1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0026
AIR FLOW RATE      428.6LB/HR/FT2,  93.0CFM/FT2  , 141.2CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9975E+04 ; BTU/HRFT2F  .3087E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   3.54246  DRY BASIS,DECIMAL  .0367256
INLET MOISTURE, DRY BASIS DECIMAL .1876
GRAIN VELOCITY FT/HR  8.58 LB/HR/FT2  413.63
[WET-BU@D/H/FT2     8.42  WET-MTON/HR/M2     2.40]


  DEPTH    TIME     AIR      ABS      REL   GRAIN      MC      MC
                    TEMP     HUM      HUM   TEMP       WB      EQ
     FT      HR       F    LB/LB DECIMAL       F PERCENT PERCENT
   0.000   0.000   295.0   .0071    .0026    54.0   15.80    .0999
    .508    .059   123.9   .0244    .2868   123.6   14.51   8.1281
   1.003    .117   114.7   .0294    .4439   114.5   14.13  10.0801
   1.502    .175   110.6   .0316    .5348   110.5   13.96  11.2028
   2.008    .234   108.5   .0327    .5866   108.5   13.87  11.8713
   2.400    .280   107.6   .0332    .6112   107.6   13.84  12.2011
INTERNAL MOISTURE AFTER DRYING FOR  .2796E+00 HR
    .1559      .1439      .1286      .1201
    THE MAX. GRAIN TEMP. IS 150.40181 F THIS HAPPENS AT  .3478E-02 HOURS
INTERNAL MOISTURE AFTER TEMPERING FOR  .2060E+01 HR
```

```
     .1385       .1371       .1369       .1369
    THE MAX.TEMPER TEMP. IS 107.56112 F THIS HAPPENS AT 0.        HOURS
                        [WET-FLOW:FT/HR INTO    10.48;FROM    10.13]
STATIC PRESSURE, IN OF H20        12.49      ;  .3108E+01 KPA
HORSEPOWER, HP/FT2    .1829 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .8032E+04 ; LB-H20/FT2 =  .3127E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1723.92 BTU/LB-H20 IF AT 40.00 F
ENERGY INPUTS, BTU/LB
         FAN(   .50 EFF)              2.13
              HEAT AIR               67.31
              MOVE GRAIN              0.00
              CUMULATIVE             69.44

WATER REMOVED, LB/LB      .0271

BTU/LB H20  2565.49     ; THIS STAGE BTU/LB H20=   2565.49


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2     1=ECHO
DEFAULT      T=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   1.000

 HOW MANY STAGES #                                          1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                  5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                      30.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                  13.8400
    GRAIN TEMPERATURE, F:                                      100.4000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 SUAREZ    DIFFUSION   EQUATION FOR SPHERICAL   MILO
          TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                 1
    INLET AIR TEMP, F:                                         245.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                .0062
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:             92.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                 6.9000
    DRYER LENGTH, FT:                                            2.4000
    OUTPUT INTERVAL, FT:                                          .5000
    TEMPERING LENGTH, FT:                                       17.0000
CP=  .3372E+00 BTU/LB/F  HFG=  .1081E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0051
AIR FLOW RATE    424.0LB/HR/FT2,  92.0CFM/FT2  , 130.3CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9904E+04 ; BTU/HRFT2F  .3065E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   2.57425  DRY BASIS,DECIMAL  .0264227
INLET MOISTURE, DRY BASIS DECIMAL .1606
GRAIN VELOCITY FT/HR  8.58 LB/HR/FT2  413.63
[WET-BU@D/H/FT2     8.14  WET-MTON/HR/M2     2.34]
```

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	245.0	.0062	.0051	100.4	13.84	.3408
.505	.059	131.6	.0227	.2172	131.3	12.57	7.1340
1.011	.118	122.4	.0274	.3345	122.3	12.19	8.7102
1.501	.175	118.3	.0296	.4028	118.2	12.02	9.5550
2.005	.234	116.0	.0308	.4462	116.0	11.93	10.0845
2.400	.280	114.9	.0313	.4688	114.8	11.88	10.3618

```
INTERNAL MOISTURE AFTER DRYING FOR  .2796E+00 HR
    .1356      .1228       .1095       .1027
    THE MAX. GRAIN TEMP. IS 157.85440 F THIS HAPPENS AT  .3125E-02 HOURS
INTERNAL MOISTURE AFTER TEMPERING FOR  .2060E+01 HR
```

```
     .1185      .1177      .1176      .1176
    THE MAX.TEMPER TEMP. IS 114.84176 F THIS HAPPENS AT O.        HOURS
                          [WET-FLOW:FT/HR INTO    10.13;FROM     9.80]
STATIC PRESSURE, IN OF H2O        12.47     ;  .3104E+01 KPA
HORSEPOWER, HP/FT2   .1807 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .6481E+04 ; LB-H2O/FT2 =  .2981E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1240.78 BTU/LB-H2O IF AT 40.00 F
ENERGY INPUTS, BTU/LB
         FAN(   .50 EFF)             2.11
              HEAT AIR              53.93
              MOVE GRAIN             0.00
              CUMULATIVE            56.03

WATER REMOVED, LB/LB      .0258

BTU/LB H2O  2171.65     ; THIS STAGE BTU/LB H2O=   2171.65


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     O=ECHO
DEFAULT
 GRAIN TYPE (O=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT       T=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   2.000

 HOW MANY STAGES #                                              2
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                      5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                         30.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                     11.8800
    GRAIN TEMPERATURE, F:                                          98.6000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 SUAREZ    DIFFUSION   EQUATION FOR SPHERICAL   MILO
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                     1
    INLET AIR TEMP, F:                                            185.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                  .0050
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:                94.7000
    GRAIN FLOW RATE, BU@D/H/FT2:                                    6.9000
    DRYER LENGTH, FT:                                               2.4000
    OUTPUT INTERVAL, FT:                                             .5000
    TEMPERING LENGTH, FT:                                           0.0000

STAGE 2 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                     5
    INLET AIR TEMP, F:                                             40.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                  .0023
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:               120.0000
STATIC PRESSURE BOUND     7.2000 IN   H20    AIRFLOW BOUND   150.0000 CFM/FT2
    GRAIN FLOW RATE, BU@D/H/FT2:                                    6.9000
    DRYER LENGTH, FT:                                               1.0000
    OUTPUT INTERVAL, FT:                                             .5000
    TEMPERING LENGTH, FT:                                           0.0000
GUESSED AIRFLOW=  .1200E+03 CFM/FT2   CORRECTED=  .1375E+03 CFM/FT2
ASSUMING AIRFLOW IN GRAIN BED AT  150.0F IS  137.5CFM/FT2
CP=  .3209E+00 BTU/LB/F  HFG=  .1112E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0137
AIR FLOW RATE    436.4LB/HR/FT2,  94.7CFM/FT2  , 122.4CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .1009E+05 ; BTU/HRFT2F  .3125E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   2.95073  DRY BASIS,DECIMAL  .0304045
INLET MOISTURE, DRY BASIS DECIMAL .1348
GRAIN VELOCITY FT/HR  8.58 LB/HR/FT2  413.63
[WET-BU@D/H/FT2     7.88  WET-MTON/HR/M2     2.29]
```

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	185.0	.0050	.0137	98.6	11.88	1.5132
.501	.058	119.2	.0140	.1905	119.0	11.14	6.9671
1.003	.117	112.7	.0171	.2782	112.6	10.88	8.1978
1.503	.175	109.6	.0186	.3298	109.6	10.75	8.8560
2.002	.233	107.9	.0194	.3620	107.9	10.68	9.2539
2.400	.280	107.0	.0199	.3796	107.0	10.65	9.4681

```
INTERNAL MOISTURE AFTER DRYING FOR  .2796E+00 HR
   .1177      .1108       .1010       .0945
   THE MAX. GRAIN TEMP. IS 134.81004 F THIS HAPPENS AT  .3134E-02 HOURS
                         [WET-FLOW:FT/HR INTO     9.80;FROM     9.60]
STATIC PRESSURE, IN OF H20       12.38      ;  .3081E+01 KPA
HORSEPOWER, HP/FT2   .1846 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .4868E+04 ; LB-H20/FT2 =  .1808E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1358.34 BTU/LB-H20 IF AT 40.00 F
ENERGY INPUTS, BTU/LB
        FAN(   .50 EFF)             2.15
             HEAT AIR              39.93
             MOVE GRAIN             0.00
             CUMULATIVE            42.09

WATER REMOVED, LB/LB     .0156

BTU/LB H20  2689.58      ; THIS STAGE BTU/LB H20=   2689.58


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE   0.00
CP=  .3111E+00 BTU/LB/F  HFG=  .1133E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   2      PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .4359
AIR FLOW RATE    520.6LB/HR/FT2, 113.0CFM/FT2  , 112.7CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .1134E+05 ; BTU/HRFT2F  .3510E+02
EQUILIBRIUM MOISTURE, WB PERCENT=  10.24155  DRY BASIS,DECIMAL   .1141012
INLET MOISTURE, DRY BASIS DECIMAL .1192
GRAIN VELOCITY FT/HR  8.58 LB/HR/FT2  413.63
[WET-BU@D/H/FT2     7.72  WET-MTON/HR/M2     2.26]
IFLOW=2 RICATTI, IFLOW=3 ASAE83D  3
```

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	133.9	.0029	.0266	107.0	10.65	3.5951
.500	.058	50.8	.0023	.2898	51.8	10.53	9.4370
1.000	.117	40.0	.0023	.4359	40.6	10.53	11.3039

```
INTERNAL MOISTURE AFTER COOLING FOR  .1165E+00 HR
    .1176      .1103       .1005       .0934
                         [WET-FLOW:FT/HR INTO     9.60;FROM     9.58]
STATIC PRESSURE, IN OF H20          7.21      ;  .1795E+01 KPA
HORSEPOWER, HP/FT2   .1283 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .2195E+03 ; LB-H20/FT2 =  .7393E-01
CUMULATIVE STANDARD SPECIFIC ENERGY   2703.16 BTU/LB-H20 IF AT 40.00 F
ENERGY INPUTS, BTU/LB
        FAN(   .50 EFF)             1.50
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```
              HEAT AIR                3.06
              MOVE GRAIN              0.00
              CUMULATIVE             46.64

WATER REMOVED, LB/LB      .0172

BTU/LB H20  2714.31     ; THIS STAGE BTU/LB H20=   2966.33


QUALITY CHANGE, PERCENT     -1     TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT      F=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [O,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[O,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   1.000

 HOW MANY STAGES #                                          1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                  5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                        32.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                    15.9000
    GRAIN TEMPERATURE, F:                                         56.0000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 PAULSEN   DRYINGRATE  EQUATION FOR THINLAYER   MILO
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (O=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                 1
    INLET AIR TEMP, F:                                           422.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                  .0096
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:               93.5000
    GRAIN FLOW RATE, BU@D/H/FT2:                                  11.4000
    DRYER LENGTH, FT:                                              2.4000
    OUTPUT INTERVAL, FT:                                            .5000
    TEMPERING LENGTH, FT:                                         17.0000
CP=  .3551E+00 BTU/LB/F  HFG=  .1088E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0007
AIR FLOW RATE    427.7LB/HR/FT2,  93.5CFM/FT2  , 165.4CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9962E+04 ; BTU/HRFT2F  .3083E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   3.49687  DRY BASIS,DECIMAL  .0362358
INLET MOISTURE, DRY BASIS DECIMAL .1891
GRAIN VELOCITY FT/HR 14.18 LB/HR/FT2  683.39
[WET-BU@D/H/FT2     13.94  WET-MTON/HR/M2     3.97]


  DEPTH    TIME     AIR     ABS     REL   GRAIN     MC      MC
                    TEMP    HUM     HUM   TEMP      WB      EQ
    FT      HR       F    LB/LB DECIMAL      F PERCENT PERCENT
  0.000   0.000   422.0   .0096   .0007   56.0    15.90   .0999
   .504    .036   135.6   .0341   .2890  135.4    14.80  7.9743
  1.003    .071   131.0   .0376   .3576  130.9    14.64  8.8460
  1.501    .106   128.2   .0397   .4068  128.1    14.55  9.4509
  2.005    .141   126.1   .0413   .4458  126.1    14.47  9.9282
  2.400    .169   124.8   .0423   .4714  124.8    14.43 10.2418
    THE MAX. GRAIN TEMP. IS 149.55744 F THIS HAPPENS AT  .1712E-02 HOURS
    THE MAX.TEMPER TEMP. IS 124.80791 F THIS HAPPENS AT O.        HOURS
                          [WET-FLOW:FT/HR INTO     17.34;FROM    16.91]
STATIC PRESSURE, IN OF H2O        13.24      ;  .3294E+01 KPA
```

```
HORSEPOWER, HP/FT2    .1949 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =   .7113E+04 ; LB-H2O/FT2 =   .2359E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1623.84 BTU/LB-H2O IF AT 42.00 F
ENERGY INPUTS, BTU/LB
         FAN(   .50 EFF)              1.38
              HEAT AIR               60.12
              MOVE GRAIN              0.00
              CUMULATIVE             61.49

WATER REMOVED, LB/LB      .0204

BTU/LB H2O  3011.80     ; THIS STAGE BTU/LB H2O=   3011.80


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2     1=ECHO
DEFAULT      F=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   2.000

 HOW MANY STAGES #                                              2
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                      5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                         32.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                     14.4300
    GRAIN TEMPERATURE, F:                                         115.2000



SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 PAULSEN   DRYINGRATE  EQUATION FOR THINLAYER   MILO
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                     1
    INLET AIR TEMP, F:                                            295.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                   .0073
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:                93.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                   11.4000
    DRYER LENGTH, FT:                                               2.4000
    OUTPUT INTERVAL, FT:                                             .5000
    TEMPERING LENGTH, FT:                                           0.0000

STAGE 2 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                     5
    INLET AIR TEMP, F:                                             40.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                   .0025
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:               120.0000
STATIC PRESSURE BOUND     9.0000 IN    H20     AIRFLOW BOUND   150.0000 CFM/FT2
    GRAIN FLOW RATE, BU@D/H/FT2:                                   11.4000
    DRYER LENGTH, FT:                                               1.0000
    OUTPUT INTERVAL, FT:                                             .5000
    TEMPERING LENGTH, FT:                                           0.0000
GUESSED AIRFLOW=  .1200E+03 CFM/FT2   CORRECTED=  .1580E+03 CFM/FT2
ASSUMING AIRFLOW IN GRAIN BED AT  150.0F IS  158.0CFM/FT2
CP=  .3422E+00 BTU/LB/F  HFG=  .1066E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0027
AIR FLOW RATE     425.5LB/HR/FT2,  93.0CFM/FT2  , 140.2CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9927E+04 ; BTU/HRFT2F  .3073E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   2.29899  DRY BASIS,DECIMAL  .0235308
INLET MOISTURE, DRY BASIS DECIMAL .1686
GRAIN VELOCITY FT/HR 14.18 LB/HR/FT2  683.39
[WET-BU@D/H/FT2    13.59  WET-MTON/HR/M2     3.90]
```

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	295.0	.0073	.0027	115.2	14.43	.0999
.523	.037	138.6	.0315	.2480	138.5	13.31	7.4237
1.006	.071	134.5	.0345	.3013	134.4	13.17	8.1360
1.510	.107	131.8	.0365	.3410	131.7	13.08	8.6430
2.004	.141	129.9	.0379	.3717	129.8	13.01	9.0241
2.400	.169	128.7	.0388	.3923	128.6	12.97	9.2783

THE MAX. GRAIN TEMP. IS 152.24132 F THIS HAPPENS AT .1475E-02 HOURS
[WET-FLOW:FT/HR INTO 16.91;FROM 16.49]
STATIC PRESSURE, IN OF H20 13.14 ; .3269E+01 KPA
HORSEPOWER, HP/FT2 .1924 (EFF= 1.00)
ENERGY AND WATER BTU/FT2 = .4801E+04 ; LB-H20/FT2 = .2268E+01
CUMULATIVE STANDARD SPECIFIC ENERGY 658.86 BTU/LB-H20 IF AT 42.00 F
ENERGY INPUTS, BTU/LB

FAN(.50 EFF)	1.36
HEAT AIR	40.15
MOVE GRAIN	0.00
CUMULATIVE	41.51

WATER REMOVED, LB/LB .0196

BTU/LB H20 2114.34 ; THIS STAGE BTU/LB H20= 2114.34

QUALITY CHANGE, PERCENT -1 TOTAL CHANGE 0.00
CP= .3299E+00 BTU/LB/F HFG= .1076E+04 BTU/LB CA= .2419E+00 BTU/LB/F

OUTPUT FOR STAGE 2 PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .4674
AIR FLOW RATE 598.0LB/HR/FT2, 130.7CFM/FT2 , 129.5CFM/FT2 [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F .1243E+05 ; BTU/HRFT2F .3847E+02
EQUILIBRIUM MOISTURE, WB PERCENT= 10.33966 DRY BASIS,DECIMAL .1153203
INLET MOISTURE, DRY BASIS DECIMAL .1490
GRAIN VELOCITY FT/HR 14.18 LB/HR/FT2 683.39
[WET-BU@D/H/FT2 13.26 WET-MTON/HR/M2 3.83]
IFLOW=2 RICATTI, IFLOW=3 ASAE83D 3

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	129.3	.0053	.0557	128.6	12.97	4.2911
.500	.035	114.4	.0035	.0550	114.7	12.85	4.5078
1.000	.071	40.0	.0025	.4674	63.5	12.78	11.2085

[WET-FLOW:FT/HR INTO 16.49;FROM 16.44]
STATIC PRESSURE, IN OF H20 8.98 ; .2236E+01 KPA
HORSEPOWER, HP/FT2 .1849 (EFF= 1.00)
ENERGY AND WATER BTU/FT2 = .1449E+03 ; LB-H20/FT2 = .1205E+00
CUMULATIVE STANDARD SPECIFIC ENERGY 1692.60 BTU/LB-H20 IF AT 42.00 F
ENERGY INPUTS, BTU/LB

FAN(.50 EFF)	1.31
HEAT AIR	1.70
MOVE GRAIN	0.00
CUMULATIVE	44.52

```
WATER REMOVED, LB/LB      .0221

BTU/LB H20  2011.14      ; THIS STAGE BTU/LB H20=   1201.63


QUALITY CHANGE, PERCENT     -1      TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT      T=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   1.000

 HOW MANY STAGES #                                          1
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                  5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                    32.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                15.9000
    GRAIN TEMPERATURE, F:                                     56.0000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 SUAREZ    DIFFUSION   EQUATION FOR SPHERICAL   MILO
           TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                 1
    INLET AIR TEMP, F:                                       422.0000
    INLET ABSOLUTE HUMIDITY RATIO:                              .0096
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:           93.5000
    GRAIN FLOW RATE, BU@D/H/FT2:                              11.4000
    DRYER LENGTH, FT:                                          2.4000
    OUTPUT INTERVAL, FT:                                        .5000
    TEMPERING LENGTH, FT:                                     17.0000
CP=  .3551E+00 BTU/LB/F  HFG=  .1088E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0007
AIR FLOW RATE    427.7LB/HR/FT2,  93.5CFM/FT2  , 165.4CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9962E+04 ; BTU/HRFT2F  .3083E+02
EQUILIBRIUM MOISTURE, WB PERCENT=   3.49687  DRY BASIS,DECIMAL  .0362358
INLET MOISTURE, DRY BASIS DECIMAL .1891
GRAIN VELOCITY FT/HR 14.18 LB/HR/FT2  683.39
[WET-BU@D/H/FT2    13.94  WET-MTON/HR/M2     3.97]


  DEPTH    TIME     AIR     ABS     REL   GRAIN     MC      MC
                    TEMP    HUM     HUM    TEMP     WB      EQ
    FT      HR       F    LB/LB DECIMAL      F PERCENT PERCENT
   0.000   0.000   422.0   .0096   .0007    56.0   15.90   .0999
    .502    .035   136.5   .0335   .2778   136.1   14.83  7.8275
   1.004    .071   126.0   .0415   .4486   125.9   14.47  9.9633
   1.505    .106   121.3   .0450   .5507   121.2   14.30 11.2347
   2.004    .141   119.0   .0467   .6085   119.0   14.22 11.9966
   2.400    .169   117.9   .0475   .6364   117.9   14.19 12.3832
INTERNAL MOISTURE AFTER DRYING FOR  .1692E+00 HR
     .1580      .1497      .1342      .1221
    THE MAX. GRAIN TEMP. IS 162.37447 F THIS HAPPENS AT  .2556E-02 HOURS
INTERNAL MOISTURE AFTER TEMPERING FOR  .1247E+01 HR
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    .1435      .1407      .1403      .1403
   THE MAX.TEMPER TEMP. IS 117.92322 F THIS HAPPENS AT 0.        HOURS
                            [WET-FLOW:FT/HR INTO    17.34;FROM    16.84]
STATIC PRESSURE, IN OF H20       13.20      ;  .3285E+01 KPA
HORSEPOWER, HP/FT2   .1944 (EFF=  1.00)
ENERGY AND WATER BTU/FT2 =  .7112E+04 ; LB-H20/FT2 =  .2740E+01
CUMULATIVE STANDARD SPECIFIC ENERGY   1503.95 BTU/LB-H20 IF AT 42.00 F
ENERGY INPUTS, BTU/LB
        FAN(   .50 EFF)              1.37
             HEAT AIR               60.12
             MOVE GRAIN              0.00
             CUMULATIVE             61.49

WATER REMOVED, LB/LB      .0237

BTU/LB H20  2592.97     ; THIS STAGE BTU/LB H20=   2592.97


QUALITY CHANGE, PERCENT     -1     TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     0=ECHO
DEFAULT
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
   3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
   7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
```

```
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 2      1=ECHO
DEFAULT      T=DTE
[SHOW F;CKDT F;  DEBUG F]SHOW=THIN MATCH; =CAPACITY(MOISTURE)SEARCH
THIN [FIND] [0,1=T,2=S,3=U;M(L),4=M;Q(R)] F 2
RECYCLE=[0,1=ENTER T'S,2= SCAN:(FROM.USED)],: 0
EITHER STAGES  OR FIND VALUES:   2.000

 HOW MANY STAGES #                                            2
 GRAIN TYPE (0=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :                    5
  INPUT IN   ENGLISH UNITS,

INPUT CONDITIONS:
    AMBIENT TEMPERATURE F:                                      32.0000
    INLET MOISTURE CONTENT, WET BASIS PERCENT:                  14.1900
    GRAIN TEMPERATURE, F:                                      120.2000


SIMULATE A CONCURRENT/COUNTER FLOW DRYER ON  04/25/85
 SUAREZ    DIFFUSION   EQUATION FOR SPHERICAL   MILO
          TEST 3 STAGE MILO

STAGE 1 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                   1
    INLET AIR TEMP, F:                                         295.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                .0073
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:             93.0000
    GRAIN FLOW RATE, BU@D/H/FT2:                                11.4000
    DRYER LENGTH, FT:                                            2.4000
    OUTPUT INTERVAL, FT:                                          .5000
    TEMPERING LENGTH, FT:                                        0.0000

STAGE 2 INPUT CONDITIONS:
    STAGE TYPE (0=NEW , 1=CONCURRENTFLOW,5=COUNTER
 2=RICATTI,3=SCOTT,4=LEREW:                                   5
    INLET AIR TEMP, F:                                          40.0000
    INLET ABSOLUTE HUMIDITY RATIO:                                .0025
RH (EITHER AMBIENT OR ENTERED) TO HEATER=      .6000
    AIRFLOW RATE,CFM/FT2   [AT AMBIENT CONDITIONS]:            120.0000
STATIC PRESSURE BOUND    9.0000 IN   H20    AIRFLOW BOUND   150.0000 CFM/FT2
    GRAIN FLOW RATE, BU@D/H/FT2:                                11.4000
    DRYER LENGTH, FT:                                            1.0000
    OUTPUT INTERVAL, FT:                                          .5000
    TEMPERING LENGTH, FT:                                        0.0000
GUESSED AIRFLOW=  .1200E+03 CFM/FT2   CORRECTED=  .1580E+03 CFM/FT2
ASSUMING AIRFLOW IN GRAIN BED AT  150.0F IS  158.0CFM/FT2
CP=  .3402E+00 BTU/LB/F  HFG=  .1065E+04 BTU/LB CA=  .2419E+00 BTU/LB/F


OUTPUT FOR STAGE   1     PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0027
AIR FLOW RATE    425.5LB/HR/FT2,  93.0CFM/FT2  , 140.2CFM/FT2  [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F  .9927E+04 ; BTU/HRFT2F  .3073E+02
EQUILIBRIUM MOISTURE, WB PERCENT=  2.20908  DRY BASIS,DECIMAL  .0225898
INLET MOISTURE, DRY BASIS DECIMAL .1654
GRAIN VELOCITY FT/HR 14.18 LB/HR/FT2  683.39
[WET-BU@D/H/FT2    13.53  WET-MTON/HR/M2     3.89]
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DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	295.0	.0073	.0027	120.2	14.19	.0999
.501	.035	143.3	.0308	.2145	143.0	13.10	6.9214
1.002	.071	133.0	.0383	.3454	132.8	12.74	8.6770
1.504	.106	128.1	.0418	.4276	128.0	12.58	9.6908
2.007	.142	125.4	.0437	.4792	125.4	12.48	10.3241
2.400	.169	124.1	.0447	.5060	124.1	12.44	10.6570

INTERNAL MOISTURE AFTER DRYING FOR .1692E+00 HR
.1406 .1311 .1163 .1059
THE MAX. GRAIN TEMP. IS 169.90200 F THIS HAPPENS AT .2094E-02 HOURS
[WET-FLOW:FT/HR INTO 16.84;FROM 16.34]
STATIC PRESSURE, IN OF H20 13.22 : .3289E+01 KPA
HORSEPOWER, HP/FT2 .1936 (EFF= 1.00)
ENERGY AND WATER BTU/FT2 = .4802E+04 ; LB-H20/FT2 = .2690E+01
CUMULATIVE STANDARD SPECIFIC ENERGY 635.52 BTU/LB-H20 IF AT 42.00 F
ENERGY INPUTS, BTU/LB
FAN(.50 EFF) 1.37
HEAT AIR 40.15
MOVE GRAIN 0.00
CUMULATIVE 41.52

WATER REMOVED, LB/LB .0233

BTU/LB H20 1783.45 ; THIS STAGE BTU/LB H20= 1783.45

QUALITY CHANGE, PERCENT -1 TOTAL CHANGE 0.00
CP= .3255E+00 BTU/LB/F HFG= .1086E+04 BTU/LB CA= .2419E+00 BTU/LB/F

OUTPUT FOR STAGE 2 PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .4674
AIR FLOW RATE 598.0LB/HR/FT2, 130.7CFM/FT2 , 129.5CFM/FT2 [AT TIN]
HEAT TRANSFER COEF BTU/HRFT3F .1243E+05 ; BTU/HRFT2F .3847E+02
EQUILIBRIUM MOISTURE, WB PERCENT= 10.26394 DRY BASIS,DECIMAL .1143793
INLET MOISTURE, DRY BASIS DECIMAL .1421
GRAIN VELOCITY FT/HR 14.18 LB/HR/FT2 683.39
[WET-BU@D/H/FT2 13.14 WET-MTON/HR/M2 3.81]
IFLOW=2 RICATTI, IFLOW=3 ASAE83D 3

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC EQ
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	PERCENT
0.000	0.000	126.0	.0083	.0947	124.1	12.44	5.3035
.500	.035	91.3	.0042	.1323	91.8	12.16	6.5519
1.000	.071	40.0	.0025	.4674	52.6	12.05	11.4159

INTERNAL MOISTURE AFTER COOLING FOR .7052E-01 HR
.1399 .1288 .1136 .0953
[WET-FLOW:FT/HR INTO 16.34;FROM 16.24]
STATIC PRESSURE, IN OF H20 8.98 : .2236E+01 KPA
HORSEPOWER, HP/FT2 .1849 (EFF= 1.00)
ENERGY AND WATER BTU/FT2 = .1449E+03 ; LB-H20/FT2 = .2465E+00
CUMULATIVE STANDARD SPECIFIC ENERGY 1447.95 BTU/LB-H20 IF AT 42.00 F
ENERGY INPUTS, BTU/LB
FAN(.50 EFF) 1.31

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            HEAT AIR                 1.70
            MOVE GRAIN               0.00
            CUMULATIVE              44.52

WATER REMOVED, LB/LB      .0284

BTU/LB H2O  1567.80      ; THIS STAGE BTU/LB H2O=    587.39


QUALITY CHANGE, PERCENT      -1      TOTAL CHANGE   0.00
UNIT TYPE [1=SI,2=ENGLISH]:
UNITS 0     O=ECHO
DEFAULT
 GRAIN TYPE (O=STOP,1=SET VIA DATA ,2=CORN
    3=RICE MEDIUM,4=RICE LONG,5=MILO,6=SOYBEANS
    7=WHEAT,8=SUNFLOWER,9=RAPESEED=COLZA :
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