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NATURAL-AIR CORN DRYING WITH STIRRING

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Natural-air corn drying with stirring

by

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SYMBOLS AND DEFINITIONS[1]

AED annual equivalent of depreciation

AEM annual operating and insurance costs

AER annual before-tax gross revenue

AEX annual after-tax net revenue

AMCA Air Moving and Conditioning Association

AR airflow ratio = $\frac{\text{airflow at a given moisture}}{\text{initial airflow}}$

ASAE American Society of Agricultural Engineers

B equipment first cost

β granule orientation factor

BCFM broken corn and foreign material; material that passes through a 4.8-mm round-hole sieve plus non-corn material larger than 4.8-mm; a quality factor used in corn trade

BD bulk density

bu bushel (1 bu corn = 56.00 lb @ 15.5% MCWB = 47.32 lb dry matter)

cfm/bu cubic feet of air per minute per bushel (for corn, 1 cfm/bu = 18.58 L/s•t)

CS computer simulation

d some characteristic particle dimension

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[1] Some definitions are unique to this dissertation--other sources may define the same term differently.

D	bin diameter
DEI	drying energy index
	$= \frac{\text{purchased energy per unit of water removed}}{\text{heat of vaporization of free water @ 20 C}}$
$\Delta P/\iota$	static pressure drop per unit of bed depth
ΔT	temperature rise
e	particle roughness factor
E	void fraction or porosity of a granular material
FT	field test
in. H_2O	inches of water pressure (1 in. H_2O = 248.7 Pa)
KD	kernel density
k_i	a numerical constant
ι	corn depth
LF	large fines; material caught between 4.8-mm and 6.4-mm round-hole sieves
L/s•t	liters of air per second per metric ton (for corn, 1 L/s•t = 0.05382 cfm/bu)
MC_i	initial moisture content, wet basis
MCWB	moisture content, wet basis
μ_f	fluid viscosity
MWPS	Midwest Plan Service
NADWIS	corn drying model for computer simulation; natural-air drying with stirring
O_f	open area in a perforated floor (decimal fraction)
P_{corn}	price of corn
P_{elec}	price of electricity

ϕ particle shape factor

points percentage points, abbreviated pt

PR percentage points of moisture removed, wet basis

Q airflow

R^2 statistical coefficient of determination

ρ_f fluid density

r/min revolutions per minute

S salvage value

SCM Shedd's curve multiplier

$= \frac{\text{measured airflow resistance}}{\text{Shedd's airflow resistance}}$

SCR Shedd's curve ratio $= \frac{\text{SCM at a given moisture}}{\text{SCM}_i}$

SEM stirring effect multiplier

$= \frac{\text{SCM after stirring}}{\text{SCM before stirring}}$

SF small fines; material that passes through a 4.8-mm round-hole sieve

SP static pressure

t metric ton (1 t corn = 1000 kg @ 15.5% MCWB = 845 kg dry matter = 39.37 bu)

τ tax bracket

TF total fines; material that passes through a 6.4-mm round-hole sieve

v horizontal speed

V — apparent fluid velocity

$$= \frac{\text{fluid volume flowrate}}{\text{inlet cross-sectional area}}$$

w.b. — wet basis

wk — week

INTRODUCTION

Stirring corn in natural-air dryers can potentially reduce drying time, spoilage, overdrying, energy use, and cost of drying.

Natural-air dryers are not normally equipped with grain stirring equipment. (See Figure 1.) With conventional natural-air drying, bin filling and fan operation begin as soon as moisture of corn in the field falls to 25%[2] or less (usually by mid-October). If the fan can provide recommended airflow for the harvest date and corn moisture, bin filling can proceed as rapidly as harvest permits.

Relatively cool outdoor air (0 to 20 C) is pulled in by the fan and forced up through the corn. Drying air is heated only by the fan (about 1 to 3 C). A drying zone develops near the floor and moves slowly upward. Corn below the zone is in approximate equilibrium with drying air while corn above the zone remains near its initial moisture content. Because the wet corn is held at low temperatures, it spoils slowly, but also dries slowly (3 to 6 weeks). Airflow must be high enough and harvest moisture low enough that corn dries before it spoils.

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[2] Unless noted otherwise, all moisture contents are wet basis.

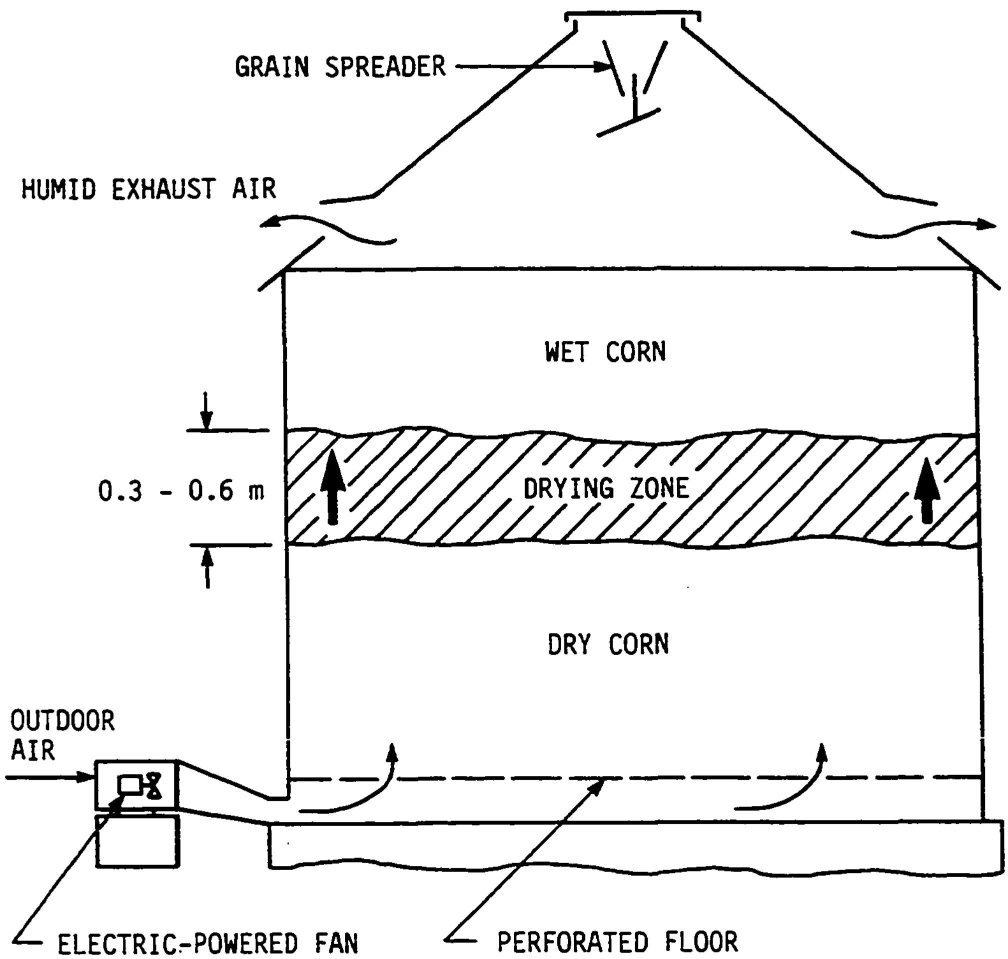


FIGURE 1. Conventional natural-air corn dryer

Natural-air drying offers several advantages over other drying methods. It allows rapid bin filling, equipment is relatively simple and trouble-free, quality of the dried corn is high, purchased energy per unit of water removed is low, and corn handling during drying is minimized. But conventional natural-air dryers also have some disadvantages. Most years, corn at bin bottom dries to less than market moisture. This overdrying reduces the weight of corn available for sale. At the same time, wet corn at the top of the bin carries a high spoilage risk, especially in unusually warm, humid fall weather.

Limited use of grain stirrers (Figure 2) in natural-air dryers can reduce overdrying, spoilage risk, and energy costs. Stirrers vertically mix grain in a bin, blending it to a nearly uniform moisture content. This reduces moisture content and thus spoilage risk of corn on top, and increases moisture of overdried corn at bottom. Grain mixing also allows turning the drying fan off when average corn moisture reaches the desired value rather than waiting for the drying zone to move all the way to the top. In some years, energy savings from early fan shut off are sizable. In addition, stirrers increase airflow through grain, which also reduces drying time and energy use.

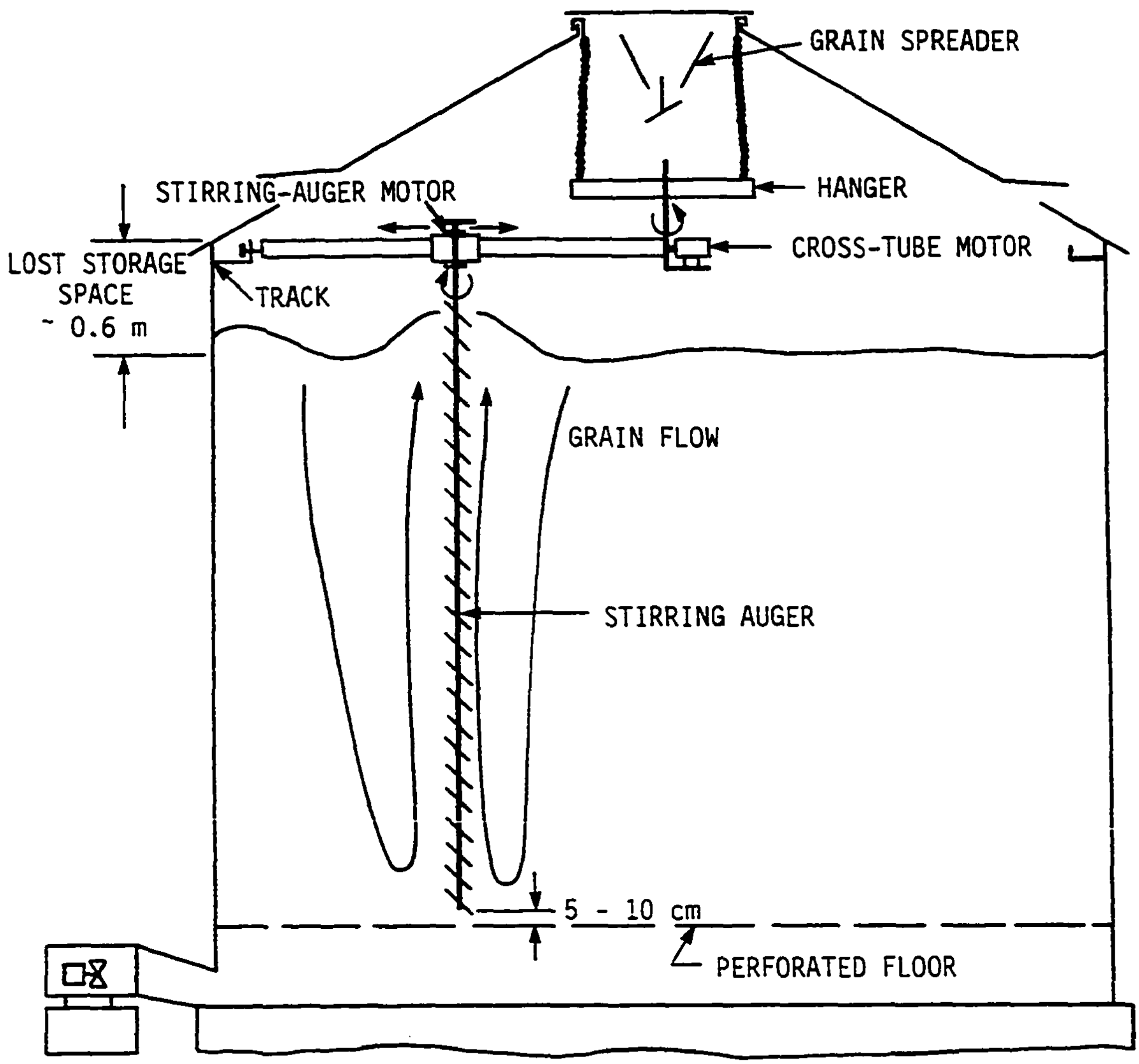


FIGURE 2. Natural-air dryer with grain stirrer

Excessive use of stirrers, however, may cause problems with fines (small pieces of broken corn and foreign material). Fines are undesirable in natural-air bins because they restrict airflow, promote spoilage, and reduce corn market value when quantity exceeds 3% of corn weight. Stirrers have been accused of creating fines by breaking corn kernels, but conclusive research results are lacking. Research does indicate that stirrers shift existing fines toward the drying floor, but effect on drying performance has not been documented.

Excessive stirring may also increase drying time and fan energy requirements. Natural-air drying has relatively low purchased-energy requirements because drying air approaches equilibrium with wet corn at the top of the bin and leaves nearly saturated. If corn is stirred after average moisture falls below about 20%, degree of air saturation decreases and drying time and fan energy use increase.

This study was undertaken to answer two major questions about natural-air stir drying:

1. How should grain stirrers be managed to maximize advantages and minimize disadvantages?
2. Are benefits from stirring large enough to justify the cost of owning and operating stirring equipment?

First, field studies were undertaken to develop and test practical stirrer management schemes and to observe the effect of stirring on fines production and movement and airflow. Next, field-test results were used to modify a computer model to simulate natural-air stir drying. Finally, the computer model was used to simulate drying with many airflow levels and weather conditions. Results were used in an economic analysis of the benefits of stirring.

LITERATURE REVIEW

Natural-Air Drying

Development

Work on natural-air crop drying in the United States began in the 1920s. It was originally called "forced-air drying with unheated air" and later "mechanical ventilation with unheated air." The term "natural drying" was reserved for processes relying on wind pressure for air movement through the crop. Ear corn, soybeans, and wheat were dried in the earliest tests. Lehmann (1926) authored the first unheated-air drying report that appears in U.S. agricultural engineering literature.

Trullinger (1927) reported on ear corn drying tests at the Illinois Agricultural Experiment Station. Researchers found that forced, unheated air worked, but was costly when weather was cold and damp. Kansas researchers found similar results when drying wheat with "cold air" (Anon., 1928). Duffee (1927) successfully dried barley in Wisconsin with unheated air. He realized the importance of adequate airflow and reported that he used 5 cfm/bu, but he did not list initial grain moisture.

Research on artificial drying of ear corn and cereal grains was largely prompted by mechanization of harvesting methods. As early as 1924, cornpicker-huskers were found to be cheaper than hand picking (Aspenwall, 1924). They worked best under slightly wet conditions, which sometimes led to a need for artificial drying. Adoption of combine harvesters for cereal grains led to harvest at moistures too high for safe storage. Ag engineers were called upon to develop inexpensive drying equipment for farmers (Wirt, 1927).

Grain drying research was also stimulated by rural electrification. Until electric power became available on farms, crop-drying fans were powered by internal combustion engines. They were not very convenient or reliable (Foster, 1950). Once electricity was available, power suppliers pressured researchers to find profitable uses for it. As a result, a lot of hay drying research with electric-powered fans was conducted in the 1930s and 40s. Experience at drying hay with unheated air facilitated corn drying research when field shelling became more common (Hukill, 1957).

Research on shelled-corn drying paralleled development of shelled-corn harvesters. McKibben (1929) reported an attempt by Iowa State College researchers to harvest drilled corn with a modified small grain combine and expressed a need for corn drying. Logan (1931) discussed further work on the corn combine along with unheated-air drying of shelled corn by Walter G. Ward at Iowa State College. Other work on unheated-air drying was reported by Kelley (1939), Barre and Kelley (1942), Shier et al. (1943), Holman and Carter (1947), Hukill (1948, 1954), Shedd (1949), Foster (1950, 1953), Hurlbut et al. (1952), and Strait and Keppel (1954). Much of this research was stimulated by the need for better drying of grain stored by the Commodity Credit Corporation, or stored on farms under government loan (McArthur, 1949).

While some researchers were conducting grain drying field studies, others worked on basic grain drying theory and grain physical properties. Hukill (1947) outlined basic principles of grain drying and a layer by layer calculation method for charting drying progress. Airflow resistance of bulk grain was studied by Henderson (1943) and Shedd (1953). Data on equilibrium moisture content and/or heat of vaporization of water from corn were collected by Henderson (1952), Johnson and Dale (1954), Thompson and Shedd (1954), Rodriquez-Arias (1956), Chung and Pfost (1967), and others. The amount of time available to dry corn at different moistures and temperatures (allowable storage time) was observed by Teter and Roane (1958), Saul and Lind (1958), Steele et al. (1969), and Saul (1970).

In addition to testing unheated-air drying, many of the pre-1970 researchers also dried grain with "supplemental heat," or air heated only 2 to 15 degrees C. Shove (1970b) used the term "low-temperature" to describe these drying methods. Shove had first tried aerating corn with unheated air and mechanically-refrigerated air (Shove and Andrew, 1969), but decided heating air a few degrees was more appropriate for corn drying in Illinois (Shove, 1970a, 1970b, 1971, 1972). He developed airflow and supplemental heat recommendations that were widely repeated in commercial grain drying literature (IFEC, 1972, 1973, 1978; Arnholt and Rupp, 1974; Iowa Power, 1974; Anderson, 1975; and FEC, 1976).

By the late 1960s, enough work had been done mathematically describing grain drying processes, grain physical properties, and air properties (Brooker, 1967), that researchers were able to develop computer grain drying models. With appropriate weather data inputs, these models could very rapidly simulate many grain dryer configurations under a wide variety of weather conditions. Bloome developed a near-equilibrium model (Bloome and Shove, 1971) that was refined by Thompson (1972) and further modified by Morey (Morey et al., 1976). These researchers used their models to develop recommendations for low-temperature drying (both airflow and amount of supplemental heat).

In 1978, the Midwest Plan Service received a grant from the U.S. Department of Energy to write a handbook on solar grain drying. (Solar drying is usually a low-temperature process.) The Plan Service assembled most of the north-central region's leading researchers on low-temperature and solar drying and had them agree on a set of recommendations for corn producers. These recommendations were printed in MWPS-22, Low-temperature & solar grain drying handbook (MWPS, 1980)--currently the most complete source of information on low-temperature drying in the north-central region.

Airflow recommendations for low-temperature dryers, 1952 to present, are presented in Table 1.

Description of natural-air drying

As mentioned in the last section, MWPS-22, Low-temperature & solar grain drying handbook (MWPS, 1980) is currently the primary source of information on low-temperature drying methods, including natural-air drying. Most of the following information is from MWPS-22.

Natural-air drying is a slow (3 to 6 weeks), in-storage drying process that usually takes place in a cylindrical bin equipped with grain spreader, full perforated floor, and positive-pressure fan powered by an electric motor (Figure 1). Drying air is heated only by the fan (about 1 to 3 C).

TABLE 1. Airflow recommendations for low-temperature corn dryers[a]

Source:	USDA	Hurlbut et al.	Strait & Keppel	CDMA	Shove
Years:	1952, 1960, 1965, 1969	1952	1954	1956	1970a
Moisture content (% wet basis)			Minimum recommended		
28					
26		3	NR[e]		NR
25	5		NR	5	NR
24.5			NR		NR
24			NR		NR
23.5			NR		NR
23			NR		NR
22.5			NR		NR
22			3		1
21.5					1
21					1
20	3			3	1
18	2			2	1
16	1				1

[a]For single-fill bins of shelled corn harvested mid-October in Iowa or areas bordering Iowa.

[b]Illinois Farm and Electrification Council, Urbana.

[c]Nebraska Inter-Industry Electric Council, Columbus.

[d]Midwest Plan Service, Iowa State University, Ames.

[e]Not recommended.

IFEC[b] (from Shove) 1972	IFEC 1973	NIIEC[c] (from Thompson) 1973	Morey et al. 1977	IFEC 1978	Pierce & Thompson 1978a	MWPS[d] 1980
airflow (cfm/bu)						
				5		
2	3		4.5	3	5.44	
						3
1.5	2	3	2.5	2	2.42	
						2
						1.5
1	1	1.5	1.5	1.25	1.47	
						1.25
		0.75	0.75	1	0.64	1
		0.375				

Grain depth is usually 3.5 to 5.5 m and full-bin airflow is usually 18 to 38 L/s•t. Suggested management is to start the fan during bin filling and run it continuously until all grain in the bin is dry, or winter weather arrives. If drying is not completed in fall, grain is cooled to about 0 C for winter storage. Drying is then completed in spring.

During drying, a 0.3- to 0.6-m drying zone develops near the floor and moves slowly up through the grain. Grain below this zone comes to approximate equilibrium with average drying-air conditions, while grain above the zone remains near its initial moisture.

Some advantages that natural-air drying provides corn producers are:

- Minimum grain handling. Equipment and labor costs and grain damage are low because grain is not moved until it is fed or sold.
- High-quality dried grain. Because relatively cool, moist air is used (compared to high-temperature dryers), corn kernels are not exposed to the high thermal and moisture gradients that cause stress cracks. Stress cracks reduce milling quality and increase breakage susceptibility of kernels.
- Less dependence on petroleum-based fuels. Petroleum-fuel shortages have occurred several

times in the last decade, while electric power has remained plentiful.

- Low purchased-energy requirements per unit of water removed. Purchased energy is used primarily for air movement--most of the drying potential comes from the natural drying potential of outdoor air.
- Unlimited harvest rate. Fans are usually sized to deliver necessary airflow with full bins, so once moisture of corn in the field is low enough, bins can be filled as rapidly as harvest permits.
- Management is size neutral. Operation is the same regardless of bin size, so natural-air dryers are equally appropriate for large or small farms.

One disadvantage of natural-air drying is that corn at bin bottom often overdries. Overdrying is defined as drying to less than market moisture, which is usually 15.5%. Corn is sold by weight, so when it is overdried, revenues are reduced--water is removed that could have been sold at the price of corn. Energy costs are also higher for overdried corn because extra water is evaporated.

Another disadvantage of natural-air drying is that corn above the drying zone is held at high moisture and thus at high spoilage risk. Even when airflow and corn moisture recommendations are followed, this wet corn can spoil in unusually warm weather. Spoilage from fungal activity consumes dry matter, results in price discounts, and under certain conditions can contaminate corn with toxins.

Grain Stirrers

Mixing effects

If moisture from wet kernels at the top of natural-air bins could be transferred to overdried kernels at bottom, overdrying and spoilage risk could both be reduced. White et al. (1972) mixed wet and dry corn kernels and found that moisture does transfer between kernels. Moisture content of each fraction came to within about one percentage point of the average moisture content of the mixture. Thus, vertically mixing corn in a natural-air dryer should bring about moisture transfer and safer, less costly drying. Pierce and Thompson (1978b) used computer simulation to study potential solutions to the overdrying problem. They concluded that mixing grain would work best.

Equipment is available to vertically mix grain in bins. In-bin grain stirrers were first marketed about 1962 (Bern, 1980). They consist of one or more bare, vertical screws about 51 mm in diameter (down augers) mounted on a horizontal support (Figure 2). One end of the support runs on a track fastened near the top of the bin wall and the other end pivots on a hanger suspended from the bin roof. Down augers are powered by electric motors and mix grain by elevating kernels from floor to surface. Another electric motor moves the auger support around the bin while moving the down augers radially along the support. This produces the spiral stirring patterns illustrated in Figure 3. Down augers move along the spiral at a horizontal speed of about 4.2 m/h.

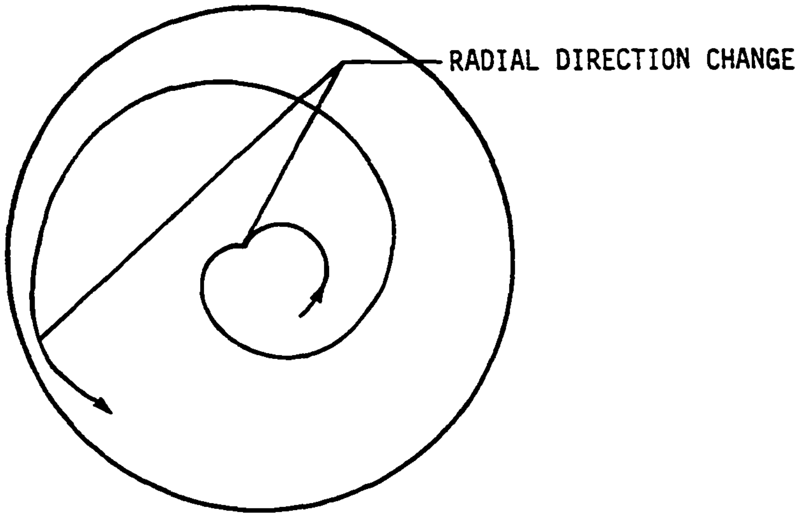
Research has shown stirrers to be effective in blending grain to a uniform moisture. Bern (1980) says that stirrers can equalize grain moistures in a bin with 24 to 48 h of operation. Hall and Beaty (1970) found a very uniform grain moisture in their stirred model bin. In solar rice drying tests, Calderwood (1977) measured a 6-point moisture variation in unstirred bins, but only one percentage-point variation in stirred bins. Stirrers limited moisture variation to 0.8 percentage points in low-temperature corn drying bins at Purdue University (Baker et al., 1979).

Airflow effects

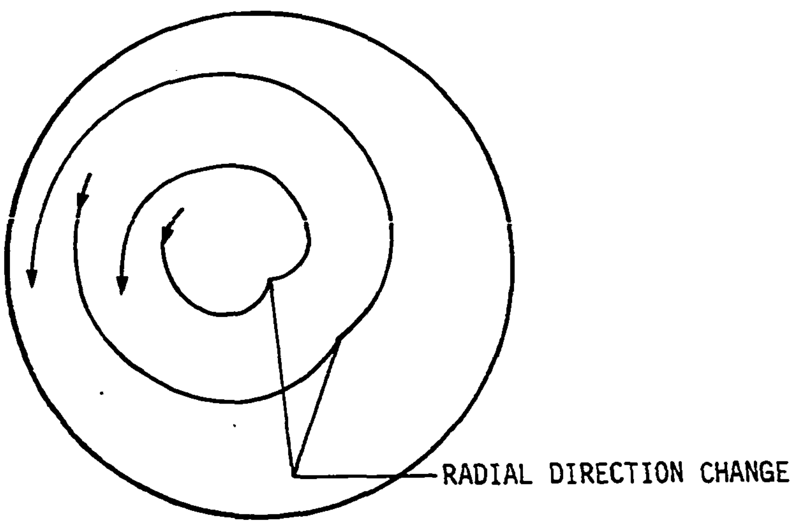
Airflow through a granular material like corn is determined by fan characteristics and the material's airflow resistance. Airflow resistance is usually expressed as pressure drop per unit depth of material, $\Delta P/\iota$.

$\Delta P/\iota = f(V,\rho_f,\mu_f,E,D,d,\phi,e,\beta)$ (Bern, 1984)

where ΔP = pressure drop across total bed depth



A. SINGLE-AUGER



B. MULTIPLE-AUGER

FIGURE 3. Approximate grain-stirring patterns

ι = total bed depth

V = apparent fluid velocity

$= \frac{\text{fluid volume flowrate}}{\text{total inlet area}}$

ρ_f = fluid density

μ_f = fluid viscosity

E = void fraction or porosity of granular material

D = bin diameter

d = some characteristic particle dimension

ϕ = particle shape factor

e = roughness factor

β = granule orientation factor

In natural-air drying, air temperature variation is generally small enough that ρ_f and μ_f can be treated as constants. D is included to account for wall effects. If D is greater than 16d, it can be neglected (Bern, 1984). For grain dried in farm-sized bins, d is about 6 mm and D is usually 5.5 m or greater ($D \geq 917d$). Shape factor, ϕ, and roughness factor, e, are generally negligible. For undisturbed grain, porosity, E, and granule orientation factor, β, are constant, so

$\Delta P/\iota = f(V,d)$.

Shedd (1953) measured the airflow resistance of various grains and presented the data as shown in Figure 4. The ordinate is V in cfm/ft^2, the abscissa is $\Delta P/\iota$ in in. water/ft, and each curve represents a different value of d.

Shedd's curves are for clean, loose-filled grain of one variety, at one moisture content. If grain variety or moisture, bin-filling method, or amount of fine material is changed, airflow resistance will be different from Shedd's value. Researchers often calculate the ratio between airflow resistance measured in their experiments and Shedd's value at the same airflow. Some researchers call this ratio a pack factor. Because the term "pack factor" is also used in discussions about bulk density changes, I will use Shedd's curve multiplier (SCM) to avoid confusion.

When non-spherical particles like corn kernels are stirred, it becomes necessary to include porosity, E, and granule orientation, β, in the airflow resistance equation. For a given lot of corn, particle diameter, d, will be constant.

$$\Delta P/\iota = f(V, E, \beta)$$

where $E = 1 - BD/KD$ (Nelson, 1978)

and BD = bulk density

KD = kernel density

At constant moisture, kernel density is also constant. So if stirring increases or decreases $\Delta P/\iota$ at a given V, the change must be caused by a change in bulk density and/or kernel orientation.

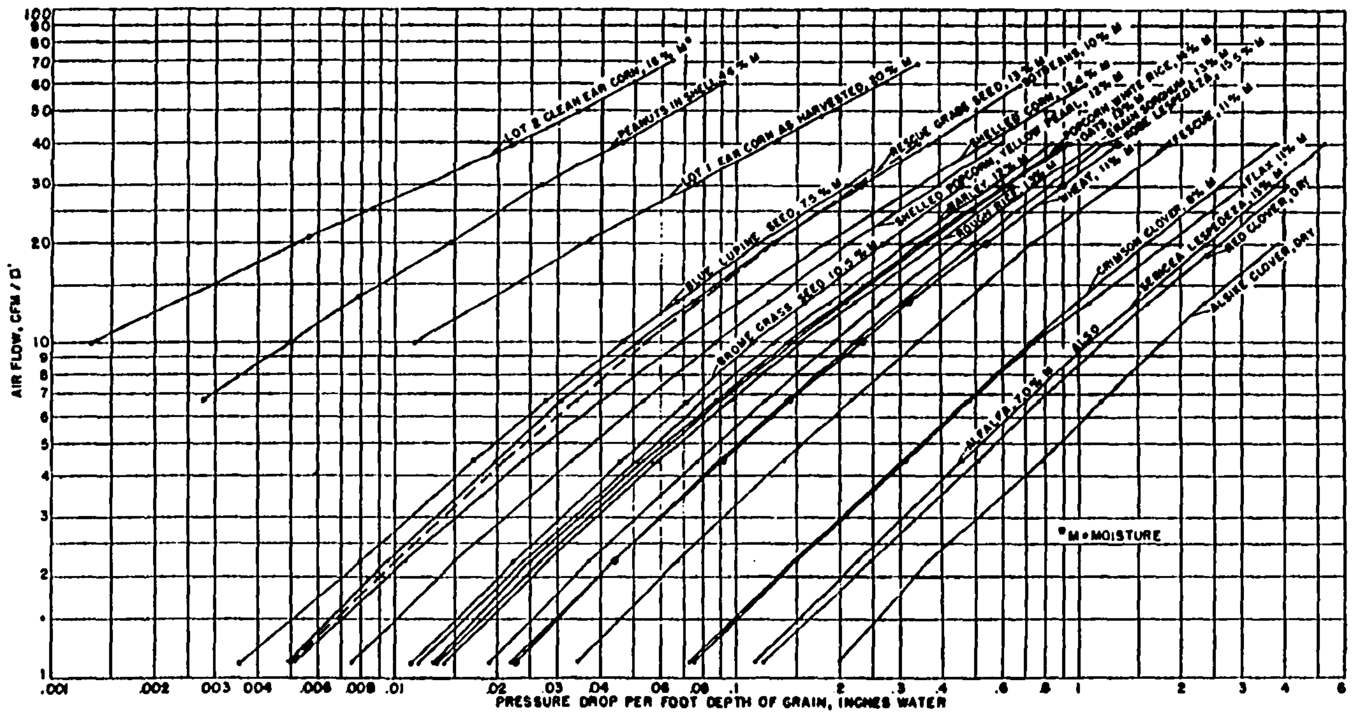


FIGURE 4. Shedd's curves (Shedd, 1953)

Ergun (1952) developed the following semi-empirical equation for airflow resistance of granular materials. β, ϕ, and e are incorporated into constants k_1, and k_2.

$$\Delta P/l = \frac{k_1 (1-E)^2 \mu_f V}{E^3 d^2} + \frac{k_2 (1-E) \rho_f V^2}{E^3 d}$$

Bern and Charity (1975) modified the Ergun equation by also lumping μ_f, ρ_f, and d into the constants. The resulting equation gives airflow resistance as a function of only porosity and airflow.

$$\Delta P/l = x_1 + \frac{x_2 (1-E)^2 V}{E^3} + \frac{x_3 (1-E) V^2}{E^3}$$

where x_1, x_2, and x_3 are regression constants.

Bern and Charity's equation was adopted as ASAE Standard D272.1 Section 5 (ASAE, 1983). The equation indicates that airflow resistance will decrease when porosity increases. Because porosity increases when bulk density decreases (at constant kernel density), this means that reductions in bulk density should decrease airflow resistance.

A number of studies have shown that stirring corn reduces airflow resistance, which generally results in greater airflow from a given fan. Toms (1968) measured up to 30% airflow increase in stirred 12% moisture corn and up to 56% airflow increase in stirred 26% moisture corn in a model bin. Bern (1973) also noted airflow increases in a similar study of stirring. In high-temperature bin-batch dryers, Frus (1968) observed lower static pressure for stirred batches. Hurburgh and Bern (1978) calculated Shedd's curve multipliers of 1.1 and 1.2 for stirred low-temperature drying bins compared to 2.2 and 1.7 for unstirred bins. Stirring wet, spreader-placed corn cut airflow resistance 50% and boosted airflow 33% in a test by Bern et al. (1982).

Only one of these studies examined effect of stirring on kernel orientation. Bern (1973) acknowledged problems with his measuring technique, but observed that stirring did not significantly change kernel orientation. He concluded that his airflow increases were caused by 6.5 to 10% bulk density reductions. Toms (1968) also measured bulk density decreases and came to the same conclusion. Part of Bern's 1982 study (Bern et al., 1982) supported the bulk density explanation. Bulk density was reduced 8% when airflow through wet, spreader-placed corn increased 33%. But stirring gravity-placed corn increased airflow 5 to 11% with no change in bulk density. Kernel orientation deserves further consideration as a factor in stirring studies.

Most research has shown that a single stirring increases airflow through corn. Additional stirrings, however, do not necessarily bring further airflow increases.

Toms (1968) found that repeated stirring did not continue to increase airflow and sometimes decreased it. Baker et al. (1979) made similar observations in their field tests. One stirring reduced static pressure 10% compared to an unstirred bin and a second stirring made it 25% lower. After that, stirring had no further effect on static pressure.

In stir-drying tests, it is difficult to separate the effect of stirring on bulk density and airflow resistance from effects brought on by grain moisture changes. Shedd (1953), Chung and Converse (1971), Patterson et al. (1971), Gustafson and Hall (1972), Hall (1972), Nelson (1978), and Haque et al. (1981) conducted lab studies on the relationships between corn moisture and bulk density, porosity, and/or airflow resistance. Their results indicate that as moisture of clean, loose-filled corn decreases, bulk density increases with a resulting decrease in porosity and increase in airflow resistance. When Patterson et al. (1971) kept corn porosity constant, however, airflow resistance decreased with moisture content. Apparently kernel shape, orientation, or surface characteristics become important when porosity is held constant.

In field tests, where bulk density and airflow resistance are measured as corn dries <u>in situ</u>, results seem to be opposite those for lab studies. Maiwald (1979) found that bulk density of an unstirred low-temperature drying bin decreased to a minimum as average corn moisture decreased from 21% to 17% and then increased as corn dried to 15% moisture. Airflow and static pressure fluctuated from day to day with no obvious trend. Converse et al. (1983) found that both bulk density and airflow resistance decreased as unstirred corn dried. Perhaps differences in filling methods, use of in situ bulk density, or use of average bin moisture caused the difference between lab and field test results.

Fines production and movement

Fines are small pieces of broken corn and foreign material. They are undesirable in natural-air bins because:

- When present in large quantities, they reduce corn market value. Corn price is usually discounted when broken corn and foreign material (BCFM) exceed 3% by weight.
- Fines spoil faster than whole kernels (Kalbasi-Ashtari, 1980).
- Fines increase airflow resistance of grain. Haque et al. (1978) and Grama et al. (1984) developed equations for pressure drop through corn as a function of percent fines.

- During bin filling, particles tend to segregate by size, so pockets of high fines concentration develop. Because these pockets of fines have high airflow resistance, drying air diverts around them and the likelihood of spoilage increases.

Some corn producers believe that stirring augers produce fines by breaking corn kernels, but little research has been conducted. Frus (1968) reported that stirrers caused no apparent grain damage in his short-term, high-temperature batch drying tests. No reports on grain damage from long-term stirring were found in the literature.

There is some evidence that stirrers shift existing fines toward the bin floor. Baker et al. (1979) suspected that fines concentration was increasing in the lower part of their stirred low-temperature bins, but data were too variable to support firm conclusions. Israel (1980) was able to document a statistically significant shift of fines to the lower half of a stirred low-temperature drying bin. He did not examine effect on airflow.

Stir-Dryer Performance and Economics

As discussed earlier, stir drying has some advantages over conventional natural-air drying. But if stirrers are to be a worthwhile investment, the value of savings from stir drying (reduced spoilage, overdrying, and energy use) must exceed the considerable cost of owning and operating stirring equipment (first cost, interest, repairs and maintenance, insurance, value of lost storage space, and electricity use). Some researchers have compared performance of stir dryers with conventional low-temperature dryers using field tests and/or computer simulation.

Hurburgh and Bern (1978) compared stirred and unstirred dryers in an on-farm test. Operating 8 h/day, a stirrer saved little drying energy in a fall with normal drying weather. The next fall, with 4 h/day stirrer operation and very dry weather, stirring greatly reduced energy use and overdrying. The authors suggested operating stirrers less after corn dried to about 20% moisture to maintain greater drying efficiency.

Baker et al. (1979) did not save energy, but did reduce spoilage by stirring a low-temperature drying bin. Continuous stirring resulted in greater electric energy use than no stirring (0.6 vs. 0.3 kWh/kg of water removed). The next year, electric energy use was the same for an unstirred bin and one stirred 24 h/wk. But enough spoilage occurred in the top of the unstirred bin to reduce corn grade from No. 2 to No. 3.

Pierce and Thompson (1978b) used a computer model to compare solutions to overdrying in low-temperature bins. Stirring looked most favorable and was predicted to reduce drying time and dry matter loss as well as overdrying.

Morey et al. (1978a) simulated natural-air stir drying using a computer. Stirring was assumed to increase airflow 20% and was predicted to reduce overdrying and maximum dry matter loss. Seven- to 14-day stirring intervals seemed preferable to continuous stirring.

Williams et al. (1978) included an economic analysis in their computer simulations. Airflow resistance was assumed to be 1.6 times greater in unstirred bins than in stirred ones. Stirring improved dryer performance (reduced overdrying and spoilage), but increased total drying cost.

Colliver et al. (1979a) examined the effect of various stirring plans (none, once during filling, once/week, once/day, and continuous) on electric energy and overdrying costs for low-temperature dryers. Their computer model predicted lowest total cost (energy + overdrying) for daily stirring. Fixed costs were not considered.

Both fixed and variable costs were considered in a computer modeling study by Loewer et al. (1984). Using some fairly conservative inputs (only 5-year stirrer life, only 10% airflow increase, high stirrer-energy use), they concluded stirrers were not economical for natural-air dryers, but were economical for systems using supplemental heat.

Summary

The literature indicates that conventional natural-air drying has many advantages, but it holds corn atop the bin at high moisture and high spoilage risk while overdrying corn at bin bottom. Commercially available grain stirrers have been shown to improve natural-air dryer performance by reducing spoilage and overdrying, with added benefits of boosting airflow and cutting energy use. It is not clear though, whether the airflow increase is sustained after repeated stirring, whether stirrers produce fines, or whether fines movement by stirrers affects airflow. Past economic analyses of natural-air stir drying have not been very positive, but inputs were unfavorable to stirring and stirrer management was not optimized.

OBJECTIVES

The overall objectives of this project were to develop management recommendations for corn producers with stirred natural-air dryers and to determine whether installing stirrers in natural-air dryers is cost effective. Specific objectives were to:

1. Measure bulk density, airflow resistance, and airflow changes in stirred and unstirred natural-air dryers during corn drying.
2. Quantify fines production and movement in stirred natural-air corn dryers.
3. Compare drying time, energy use, and overdrying in stirred and unstirred test bins.
4. Modify a computer model so that it accurately simulates natural-air stir drying.
5. Simulate natural-air drying with various airflow levels and stirring schemes using 20 years of Des Moines, Iowa weather data.
6. Compare net revenues for stirred and unstirred natural-air drying.

FIELD TESTS

To accomplish the first three objectives, field tests comparing stirred and unstirred natural-air corn drying were conducted during the 1982-83 and 1983-84 drying seasons.

Equipment

Corn was dried in three identical 5.5-m diameter by 5.7-m high metal bins at the Iowa State University Woodruff Farm 9 km southwest of Ames. They will be identified as the "east," "center," and "west" bins. Each bin was equipped with a full perforated drying floor and a David Bin Level model 918 motor-powered grain spreader.[3] Meter sticks permanently mounted inside each bin wall were used to measure grain depth. Static pressure in the bin plenums was measured with Magnehelic pressure gauges plumbed to piezometer rings. Each piezometer ring consisted of 9.5-mm outside-diameter copper tube that encircled the bin connecting pressure taps spaced 120 degrees apart (three per bin).

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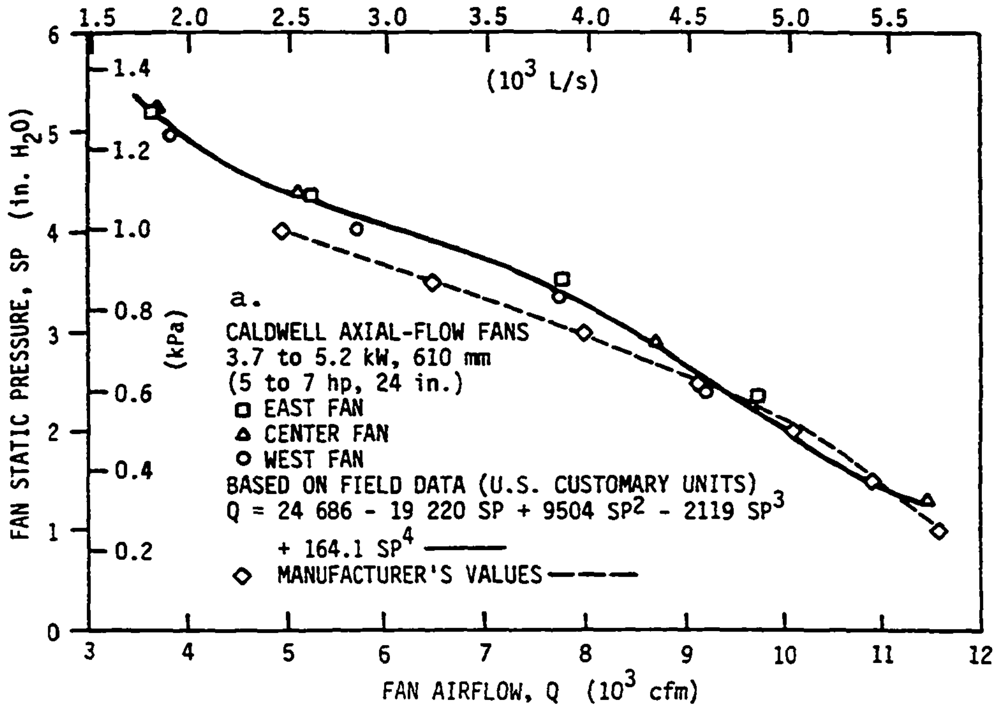
[3] Reference to a company or product name is for specific information only and does not imply approval or recommendation of the product to the exclusion of others that may be suitable.

In both years, drying air was forced up through the bins by electric-powered, axial-flow fans. The first year, each bin was equipped with a Caldwell 3.7- to 5.2-kW (5- to 7-hp), 610-mm diameter fan. A performance curve for this model fan (Figure 5a) was developed by testing the fans in place on the bins. During the fan tests, a smooth 610-mm diameter, 6.1-m long tube was attached to the fan inlet and airflow measured using a pitot tube traverse at various levels of fan static pressure. Static pressure was varied by changing corn depth in the bins. Test procedures followed AMCA Standard 210-74 (AMCA, 1975) except that no air straighteners were used in the inlet tube. Data from the three fans were very consistent and so were pooled to develop a single fan curve (Figure 5a). Field data were fairly close to manufacturer's published values--especially at static pressures less than about 0.7 kPa.

In the 1983-84 test, the Caldwell fan on the east bin was replaced by a Rolfes 2.2-kW (3-hp), 457-mm diameter fan. Time did not permit testing the new fan, so manufacturer's values were used (Figure 5b).

The east and center bins were equipped with Sukup Stir-Up, single-auger stirring machines. Down augers were bare 51-mm diameter, right-hand screws with 25-mm diameter shaft and constant 70-mm pitch. Electric 1.1-kW (1.5-hp) motors



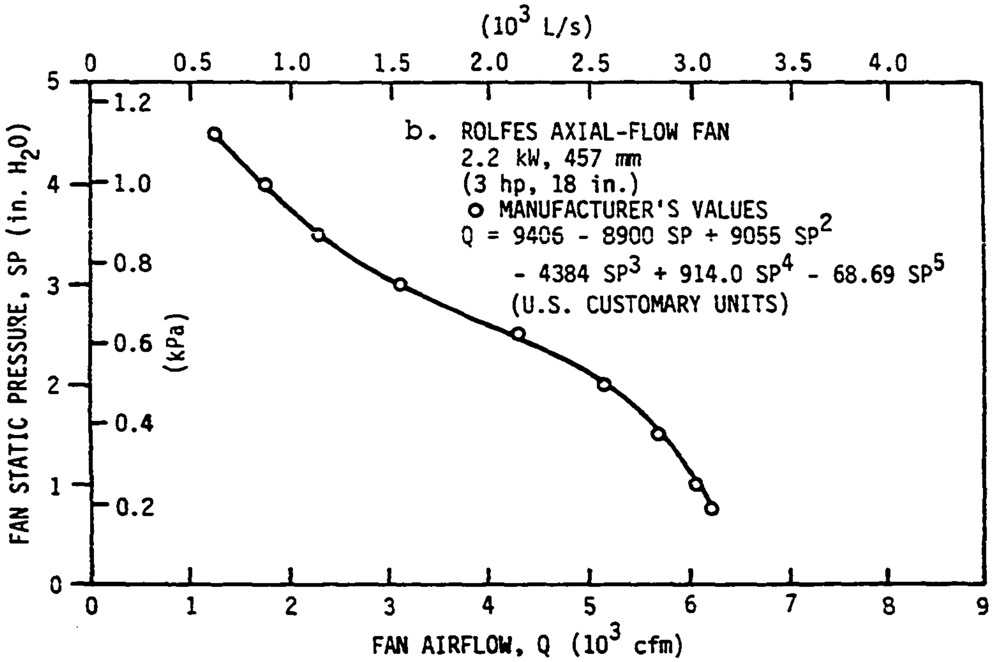


FIGURE 5. Fan performance curves

turned the down augers about 513 r/min. In the east bin, the support tube was driven by two 0.19-kW (0.25-hp) motors. The stirrer in the center bin was a newer model and had only one 0.19-kW motor on its support tube. Figure 2 is a schematic of the stirrers. In each bin, the down auger moved along a spiral path (Figure 3a) at a horizontal speed of about 4.2 m/h.

Procedure

Bins were filled October 21-22, 1982 and October 13-14, 1983 with about 75 t wet, shelled, yellow dent corn (Pioneer 3382) per bin. Exact corn quantities and average moisture contents are listed in Table 5. Corn quantity was intended to be the same in each bin and was determined by the maximum amount that would allow trouble-free operation of the stirrers. This meant initial corn depth in the unstirred bin was only about 4.3 m, which left nearly 1 m unused depth. Loads containing about 10 t wet corn were alternated among bins in an effort to produce similar fines and moisture profiles in each bin. Similar 203-mm diameter screw conveyors were used to fill each bin.

One pelican sample was taken per 1.25 t as wagons were unloaded. Accumulated pelican samples were split with a Boerner divider to produce one 3-kg sample per 10-t load for analysis at the Iowa State University Grain Quality Lab. Sample moisture was measured using the 72-h, 103 C air-oven test (ASAE Standard 352.1 (ASAE, 1983)) and fine material content was determined using a Carter dockage tester equipped with 4.8-mm and 6.4-mm round-hole sieves.

Drying fans were started during bin filling and operated continuously (except during several power outages) until average daily temperatures fell below freezing. Corn was aerated once during winter 1982-83 (25 h) and twice during winter 1983-84 (53 h). In both field tests, drying was completed in April and bins were emptied in summer.

During drying, plenum static pressures were manually recorded about once a day and grain depths once or twice a week. Corn depths were always measured just before stirring, and just after stirring and hand leveling of the corn surface. Each bin was probed in three locations, once a week, with a Cargill Prob-A-Vac. Samples were taken at five depths (surface; 1.2 m, 2.4 m, and 3.6 m down; and floor) per location. The three samples from each depth were then mixed to give one composite sample at each depth per bin. A Carter dockage tester was used to determine fines content and a DICKEY-john GAC II was used to measure moisture.

Drying was considered complete when moisture content of all samples was 15.5% moisture or less. After drying, corn was removed from the bins and sold. Pelican samples were taken during bin unloading and analyzed for final fines and moisture (air-oven) content.

Stirring plans

The west bin was the control and was operated as a conventional, unstirred natural-air dryer both years.

In 1982-83, the east bin was used to test the effect of frequent stirring. It was believed that continuous stirring would cause excessive fines shift (Israel, 1980) and poor drying efficiency (Morey et al., 1978a), so one stirring per week was selected. Stirring periods of 48 h were chosen based on Bern's (1980) statement that stirrers can completely mix grain in 24 to 48 h of operation. The east bin was stirred about 48 h during bin filling, 48 h/wk during drying, and another 48 h when average moisture fell below 15.5%.

Research has shown that limited stirring can increase airflow and reduce overdrying and spoilage, but too much stirring can reduce airflow and drying efficiency and cause fines problems. A three-time stirring plan was developed that was intended to provide the benefits of stirring while minimizing hours of stirrer operation. This plan was tested in the center bin in 1982-83. The bin was first stirred for 48 h after filling to increase airflow. It was stirred another 48 h when average moisture reached about 20% to reduce spoilage risk of the top layer, yet allow air to leave nearly saturated. Finally, the bin was stirred 48 h when average moisture fell below 15.5% to reduce overdrying and allow earlier fan shut off.

In 1983-84, corn was drier at harvest, so a two-time stirring plan was tested in the east and center bins. The bins were to be stirred 48 h during bin filling and another 48 h when average moisture reached 15.5%.

Stirring plans are summarized in Table 2.

Results and Discussion

As the footnotes to Table 2 indicate, actual stirring deviated from the plans listed. In 1982-83, the deviation was caused by too infrequent sampling and too slow sample analysis. Bins were only probed once a week and sample moistures were not returned to me for 1 to 3 days. This procedure allowed corn to get drier than intended before the second stirring in the center bin (19% instead of 20%) and before final stirring and fan shut off in both stirred bins (14.10% in the east bin and 13.65% in the center bin instead of 15.5%). In 1983-84, a hand-held moisture tester

TABLE 2. Stirring plans for field tests

Bin	1982-83	1983-84
East	48 h during filling 48 h/wk during drying 48 h @ ~15.5% avg. MCWB[a]	48 h during filling 48 h @ ~15.5% avg. MCWB
Center	48 h after filling 48 h @ ~20% avg. MCWB[b] 48 h @ ~15.5% avg. MCWB[d]	48 h during filling 48 h @ ~15.5% avg. MCWB[c]
West	No stirring	No stirring

[a]Actually stirred at 14.10% MCWB.

[b]Actually stirred at 19% MCWB.

[c]Actually stirred at 16% and again at 15.18% MCWB (three stirrings instead of two).

[d]Actually stirred at 13.65% MCWB.

indicated that the center bin was dry in late fall, so the bin was stirred and the fan turned off. Later probing showed the moisture was still 0.5 percentage points too high, so drying was completed and the bin restirred in spring. Although the results that follow show that stirred bins used less electric energy than unstirred, the savings could have been even greater with more timely stirring.

Bulk density, airflow resistance, and airflow

Raw airflow and airflow resistance data from the field tests are listed in Tables A1 to A6 in Appendix A. Values are quite variable and are a function of weather, initial corn moisture, corn quantity, and fan characteristics. An attempt was made to generalize the data to make results independent of some of these factors and thus more useful in studies where weather, moisture, corn quantity, and fan type differ. Plotting Shedd's curve ratio (SCR) as a function of wet basis percentage points of moisture removed (PR) seemed most general. SCR is the ratio of Shedd's curve multiplier (SCM) at a given time during drying to the initial SCM calculated immediately after bin filling (unstirred bins) or after the first stirring. Results are presented in Figures 7, 9, and 11.

Airflow ratio (AR) is plotted as a function of points of moisture removed (PR) in Figures 6, 8, and 10. AR is the ratio of airflow at a given time during drying to initial airflow after bin filling (unstirred bins) or after the first stirring. AR is somewhat dependent on fan characteristics and so not as general as SCR. But the equations for AR vs. PR were useful in computer simulation and are applicable when the fan performance curve is parallel to the ones in this study (Figure 5).

Data points in Figures 6 to 11 represent the average SCR or AR for three consecutive days. Static pressure readings were affected by wind speed and direction and sometimes varied greatly from one day to the next. Using average values helped smooth day-to-day fluctuations. Calculation followed these steps:

1. Daily static pressure readings were adjusted to account for differences in air density from the standard value (1.20 kg/m^3).

   $$SP_{corrected} = \frac{(\text{standard air density})}{(\text{actual air density})} (SP_{measured})$$

   Actual air density was read from a chart in AMCA 210-74 (AMCA, 1975) using barometric pressure and wet and dry bulb temperatures from Des Moines, Iowa weather records. Des Moines is about 65 km south of the test site.
2. Total fan airflow was calculated by inputting adjusted static pressure to the fan equation (Figure 5).

3. Airflow resistance (pressure drop per unit depth) was calculated from adjusted static pressure and most recently measured grain depth.
4. Dividing airflow resistance by Shedd's value at the same airflow (Figure 4) produced SCM.
5. Average airflows and SCMs were calculated from values for the day of the moisture probe, the day before, and the day after.
6. Average airflow and SCM were divided by initial values to get AR and SCR.
7. PR was calculated by subtracting average bin moisture (based on probe values) from initial average moisture.

For each bin, SCR and AR data from both years were plotted on the same graphs. The fact that data from both years seem to follow the same trend lines--despite weather and initial moisture differences--indicates that using SCR, AR, and PR has generalized the results. Data from both years were pooled and input to a Statistical Analysis System (SAS) program for development of regression equations. Equations, coefficients of determination (R^2), and curves drawn from the equations are shown in Figures 6 to 11. In a few cases, third order equations gave slightly better R^2 values, but second order equations were selected for uniformity and simplicity.

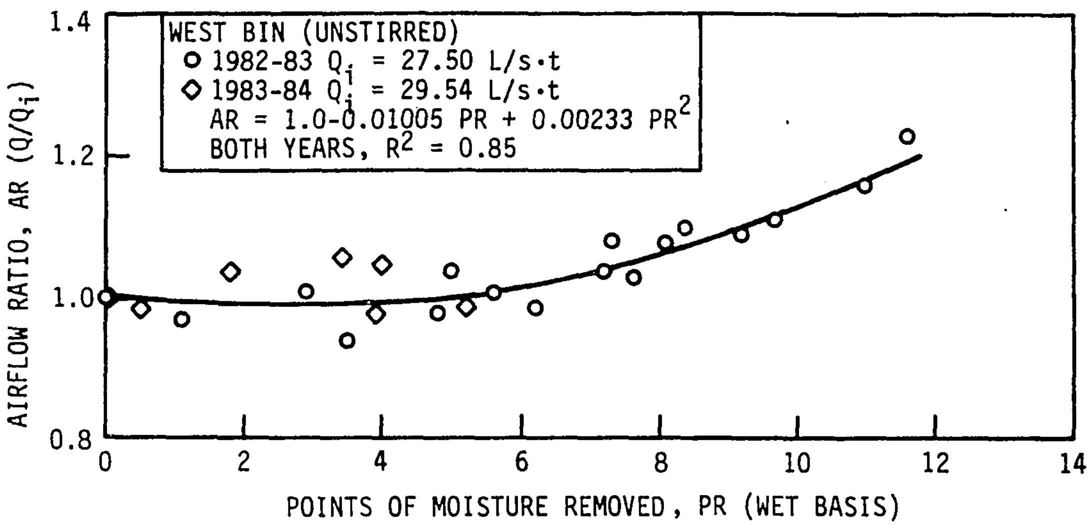


FIGURE 6. Airflow through unstirred corn

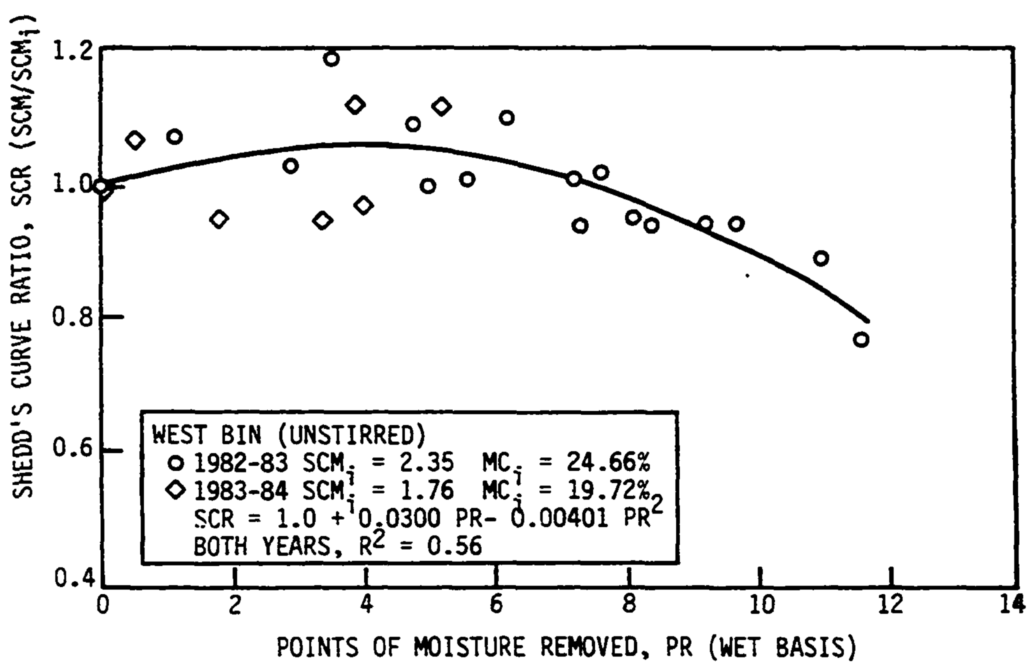


FIGURE 7. Airflow resistance of unstirred corn

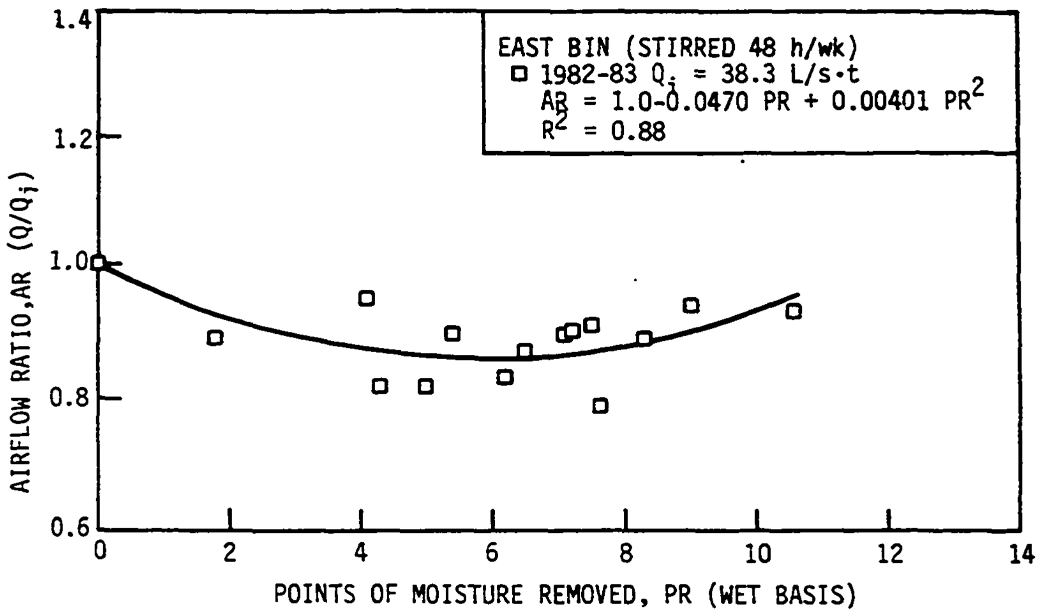


FIGURE 8. Airflow through corn stirred weekly

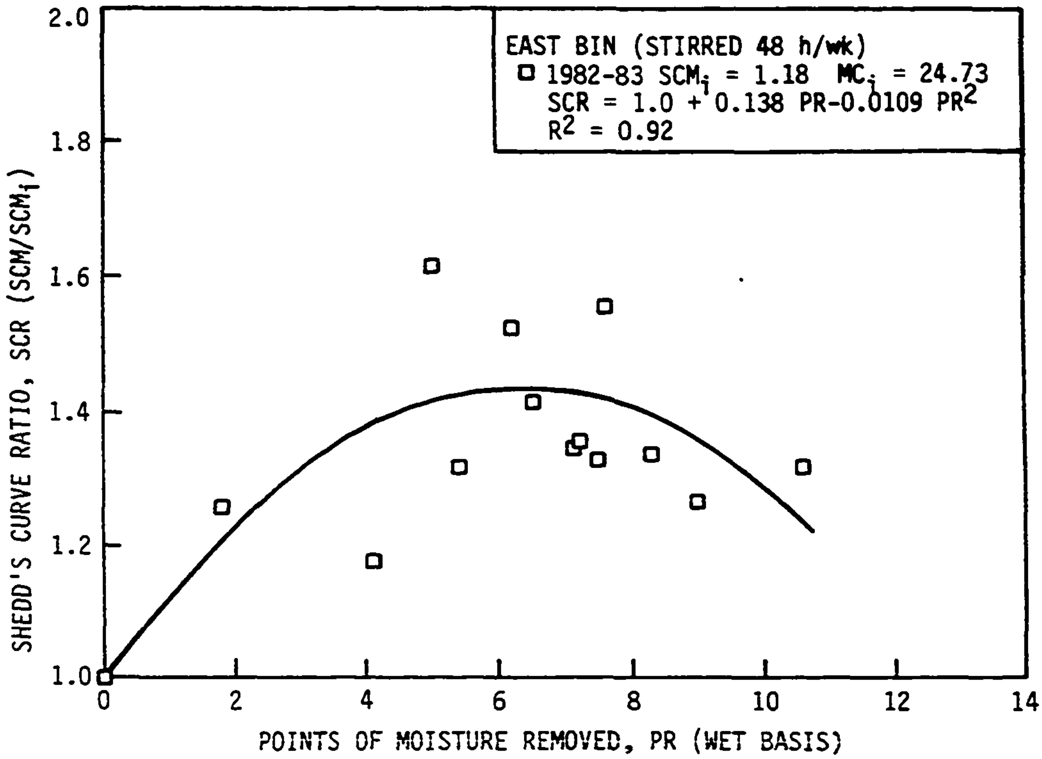


FIGURE 9. Airflow resistance of corn stirred weekly

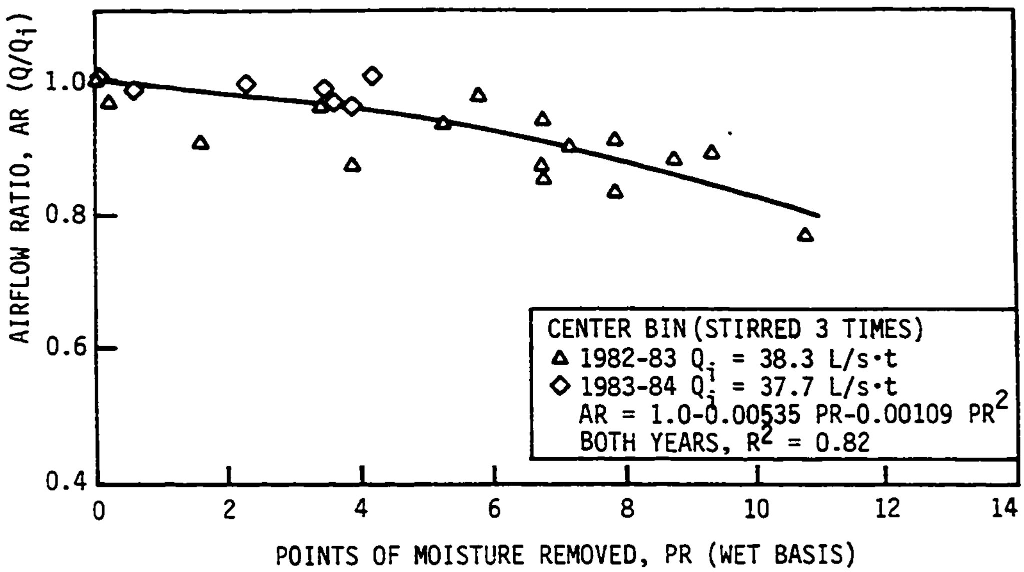


FIGURE 10. Airflow through corn stirred three times

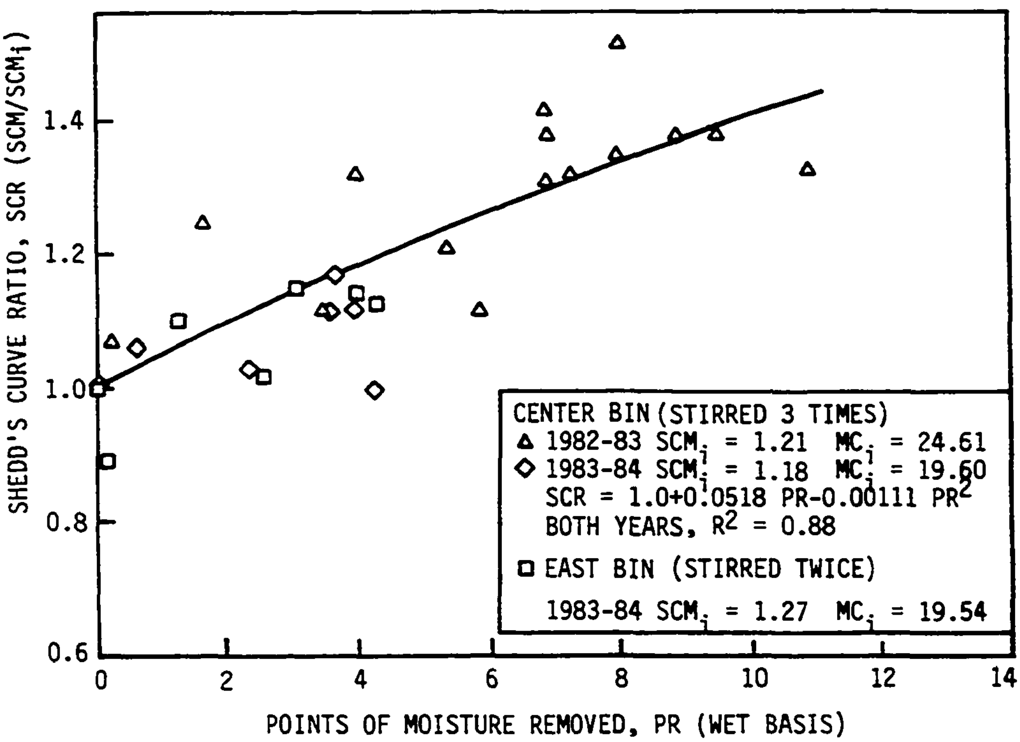


FIGURE 11. Airflow resistance of corn stirred three times

to have much higher initial bulk density than wet corn when both were spreader-placed. Large differences in growing-season weather between the two years might have produced differences in kernel size, shape, or density that influenced bulk density results. Unfortunately, this hypothesis cannot be tested because kernel properties were not measured in the field tests.

Figure 12 shows that both years, average in situ bulk density of the unstirred corn decreased as it dried. Converse et al. (1983) observed a similar trend, as did Maiwald (1979) for drying to 17% moisture. The 1982-83 field data were used to develop an equation for bulk density as a function of moisture content (Figure 12).

According to Bern and Charity (1975), decreasing bulk density should decrease airflow resistance and thus, Shedd's curve multiplier. Figure 13 indicates that in 1982-83, SCM did decrease as bulk density decreased. Data for 1983-84 show no clear trend.

SCM values predicted by Bern and Charity's equation were also plotted on Figure 13. Because kernel density was not measured in the field tests, two separate estimates were made. First, Nelson's (1978) relationship between kernel density and moisture content and my equation for bulk density vs. moisture content were used to calculate KD and

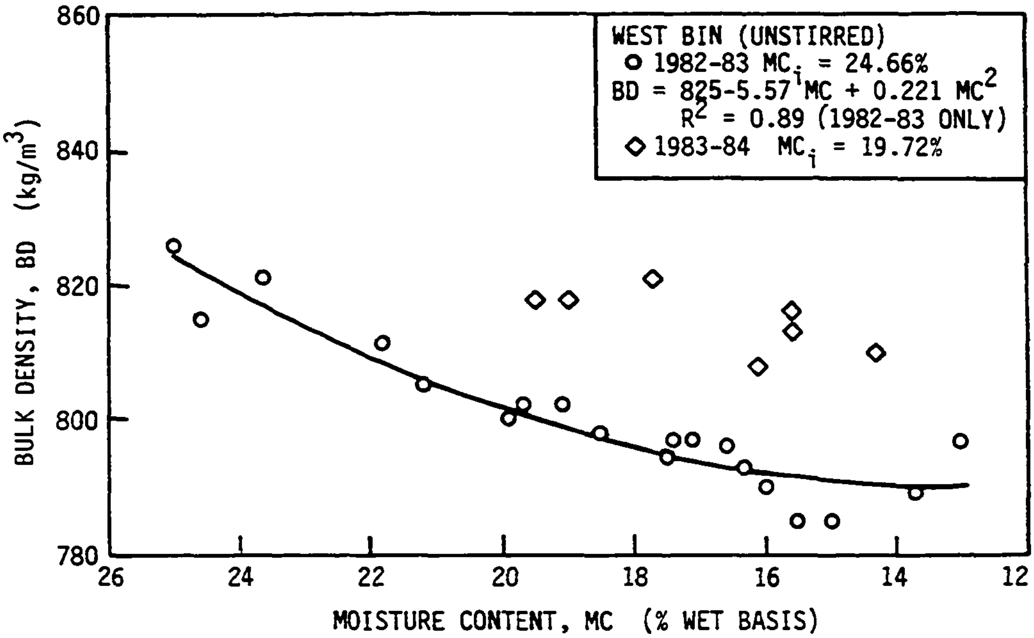


FIGURE 12. *In situ* bulk density of unstirred corn during drying

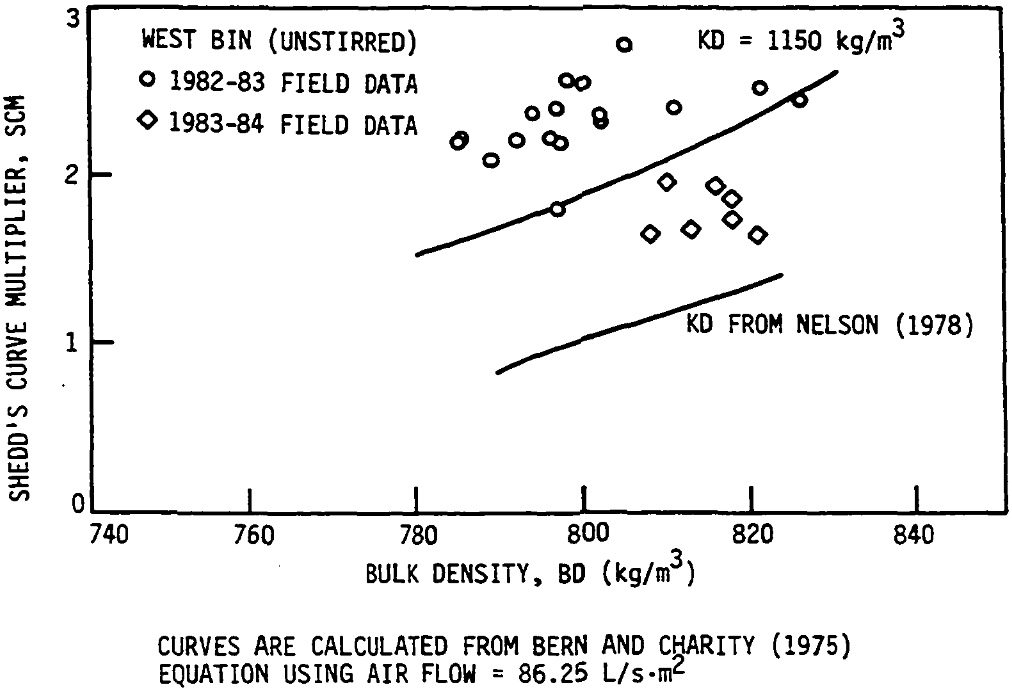


FIGURE 13. Shedd's curve multiplier vs. *in situ* bulk density for unstirred corn

BD at several moisture levels. (See lower curve.) KD ranged from 1227 to 1267 kg/m^3. These KD values agree with values published by Chung and Converse (1971), Gustafson and Hall (1972), and ASAE (1983). But as you can see, Nelson's KD values give SCM values considerably less than those measured in the field tests. Bern and Charity (1975) found an average KD of 1170 kg/m^3 for their corn samples. Using KD = 1150 kg/m^3 gives much better agreement (upper curve), but predicted SCM is still low. Apparently KD of field test corn was very low or some other kernel property differed from corn used by Bern and Charity in developing their equation.

Weekly stirring In 1982-83, the east bin was stirred during bin filling and once a week during drying. After the first stirring, SCM was about half that in the unstirred bin (1.18 vs. 2.35). The next few stirrings increased SCM (Figure 9 and Table 3). Airflow resistance decreased during the last half of the drying period, but never returned to the initial level. Even though repeated stirring kept SCM above the initial value, SCM for this bin was nearly always less than that for the unstirred bin.

After the first stirring, airflow was 39% greater than in the unstirred bin containing the same amount of corn and equipped with the same model fan. Airflow decreased with subsequent stirrings, but returned to initial values by season's end (Figure 8).

Table 3 and Figure 14a indicate that the relationship between SCM and bulk density is quite erratic for the east bin. Assuming kernel density equalled 1150 kg/m^3 and using Bern and Charity's equation gives a curve that does pass through the field data, but with a great deal of scatter. The scatter is probably caused at least in part by the effect of stirring on kernel orientation and fines.

Three-time stirring In the 1982-83 test, the center stirrer was not started until after the bin was full. Bulk density and SCM before stirring were very close to initial values for the unstirred bin: BD_{center} = 817 kg/m^3, BD_{west} = 815 kg/m^3, SCM_{center} = 2.43, SCM_{west} = 2.35. After the first stirring of the center bin, BD and SCM were very close to values for the east bin, which was stirred during filling: BD_{center} = 777 kg/m^3, BD_{east} = 764 kg/m^3, SCM_{center} = 1.21, SCM_{east} = 1.18. It seems reasonable to assume that prestirring BD and SCM for the east bin would have been similar to those in the center and west bins. Thus, stirring during filling appears to have the same effect as stirring after bin filling. Stirring during filling is much preferred and is recommended, because starting stirrers in full bins of wet corn is difficult and can damage the stirrer.

TABLE 3. Effect of stirring on bulk density, airflow, and airflow resistance

Bin	Stirring period[a]	Average moisture (% wet basis)	Bulk density[b] (kg/m^3) Before	After	% Change
East 1982-83	1	24.7	--[d]	764	--
	2	23.9	782	779	-0.4
	3	20.5	775	773	-0.2
	4	19.5	782	781	-0.1
	5	18.4	781	773	-1.0
	6	17.6	775	779	+0.6
	7	17.1	777	762	-2.0
	8	16.0	763	770	+0.9
Center 1982-83	1	24.5	817	777	-5.0
	2	18.9	774	779	+0.6
East 1983-84	1	19.5	--[d]	785	--
	2	15.5	792	788	-0.5
Center 1983-84	1	19.3	--[d]	787	--
	2	15.8	801	792	-1.2
	3	15.3	796	788	-1.0

[a]Each stirring period equals about 48 hours.

[b]Bins were filled using mechanical spreaders.

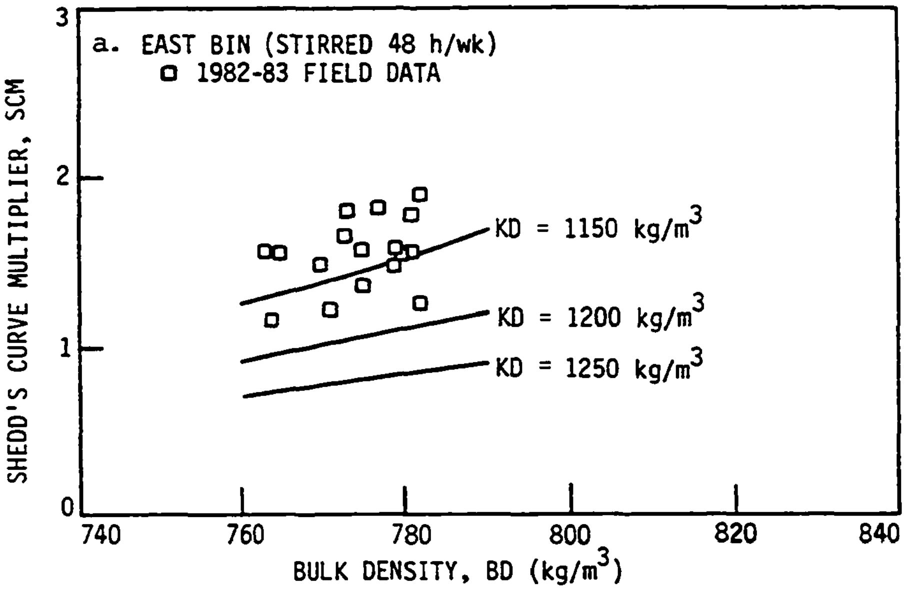
[c]Stirring effect multiplier = (SCM after stirring)/(SCM before stirring)

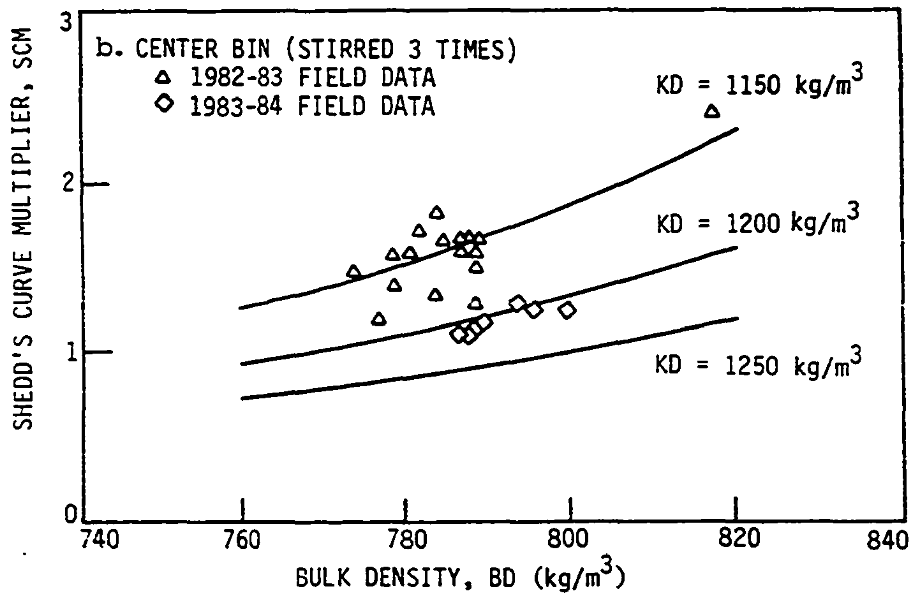
[d]Stirrer operated during bin filling.

[e]Airflow produced by a 610-mm axial-flow fan with 3.7- to 5.2-kW motor.

[f]Airflow produced by a 457-mm axial-flow fan with 2.2-kW motor.

Airflow (L/s•t)			Shedd's curve multiplier		
Before	After	% Change	Before	After	SEM[c]
--	38.1	--	--	1.18	--
38.1[e]	34.2	- 9.9	1.26	1.49	1.18
36.4	31.4	-13.6	1.39	1.82	1.31
31.2	34.6	+11.0	1.91	1.56	0.81
31.6	33.4	+ 5.7	1.81	1.68	0.93
34.4	34.4	0.0	1.59	1.60	1.01
30.1	35.9	+19.0	1.84	1.57	0.85
34.0	36.0	+ 6.3	1.58	1.50	0.95
27.1[e]	38.3	+41.3	2.43	1.21	0.50
35.7	37.3	+ 5.0	1.47	1.35	0.92
--	24.4	--	--	1.27	--
23.4[f]	24.3	+ 4.2	1.45	1.44	0.99
--	37.7	--	--	1.12	--
36.2[e]	26.4	+ 0.8	1.25	1.31	1.05
36.4	38.6	+ 6.2	1.26	1.12	0.89





CURVES ARE CALCULATED FROM BERN AND CHARITY (1975) EQUATION USING AIRFLOW = 110.4 L/s·m^2

FIGURE 14. Shedd's curve multiplier vs. in situ bulk density for stirred corn.

Starting stirrers in full bins also encourages unsafe practices. For example, it is tempting to use a pipe wrench to start a stalled down auger while the power is on. When the three-time stirring plan is used, there is a chance that the stirrer will not start on its own for the second stirring. (It should start without assistance the third time when the corn is dry.) Operators should resist the temptation to use unsafe practices and follow manufacturer's instructions for starting stalled stirrers.

After the first stirring, airflow resistance increased (Figure 11) and airflow decreased (Figure 10) throughout drying. In general though, airflow resistance was lower and airflow greater than that in the unstirred bin.

Initial stirring in the center bin increased airflow 41.3% and cut airflow resistance in half in 1982-83 (Table 3). With drier corn in 1983-84, effects from the initial stirring were not as large--airflow was 128% and airflow resistance was 64% of initial values in the unstirred bin.

The large initial airflow increase and airflow resistance decrease in the center bin in 1982-83 were accompanied by a 5% bulk density decrease. After that, the relationship between bulk density and airflow resistance became somewhat erratic (Table 3 and Figure 14b). As with the east bin, predicted SCM values from Bern and Charity's equation and an assumed kernel density of 1150 kg/m^3 passed through the 1982-83 data, but with quite a bit of scatter. Again, fines and changes in kernel orientation may have been a factor. Data for 1983-84 fall fairly close to the Bern and Charity curve when KD is assumed to equal 1200 kg/m^3. This supports the belief that kernel density was different the second year.

Effect on fines

The small pieces of broken corn and foreign material (weed seeds, chaff, soil, etc.) mixed with whole corn kernels are called fines. As discussed in the Literature Review, fines are undesirable because they reduce corn market value, restrict airflow, and increase spoilage susceptibility. Initial fines concentration in shelled corn is determined largely by combine-harvester operation--concave clearance, cleaning-air volume, and sieve setting. After harvest, fines concentration is generally increased by insect activity and kernel damage from drying and handling.

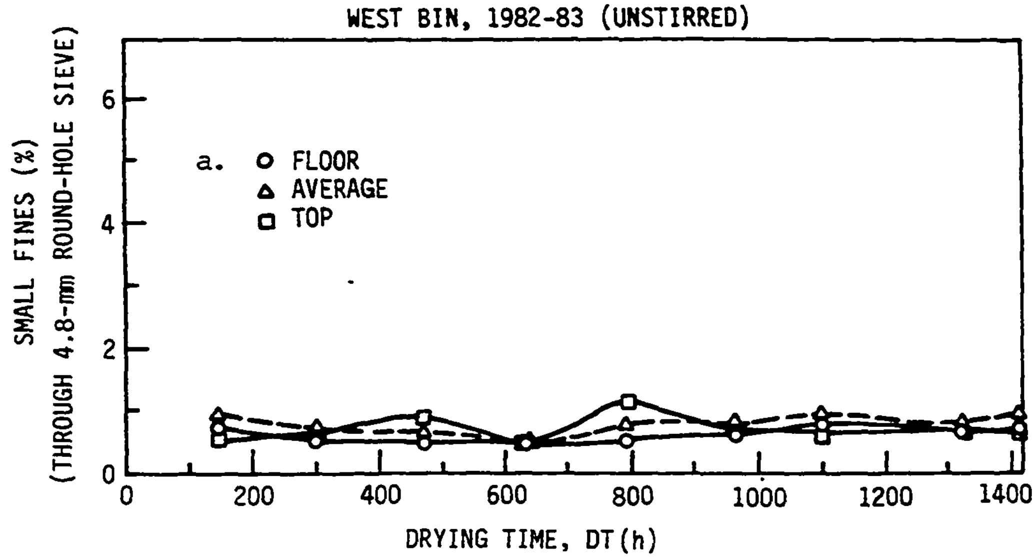
Fines concentrations were monitored during the field tests to determine whether stirring produced and/or moved fines in the drying bins. Several categories were monitored:

- Small fines (SF): broken corn and foreign material small enough to pass through a 4.8-mm (12/64-in.) round-hole sieve.

- Commercial BCFM: broken corn and foreign material that pass through a 4.8-mm round-hole sieve plus larger pieces of foreign material retained on the sieve. Not much large foreign material was present in the field tests, so BCFM and SF were essentially the same.
- Large fines (LF): material that passes through a 6.4-mm (16/64-in.) round-hole sieve, but is retained on a 4.8-mm sieve. This fraction was monitored to determine whether effect of stirrers on fines varied with particle size.
- Total fines or fines (TF): large fines + small fines.

Fines movement Figures 15, 16, and 17 show fines concentration in probe samples taken during drying. Data points are for the top of the bin, drying floor, and average for all five depths probed.

As expected, there was little evidence of fines movement in the unstirred bin (Figure 15). Fines concentration was quite uniform with depth on each probe date. Fines concentration at all depths increased slightly during drying. This may be explained by kernel breakage caused by drying stresses or more likely, by particle shrinkage during drying which allowed more particles to fall through the sieves.



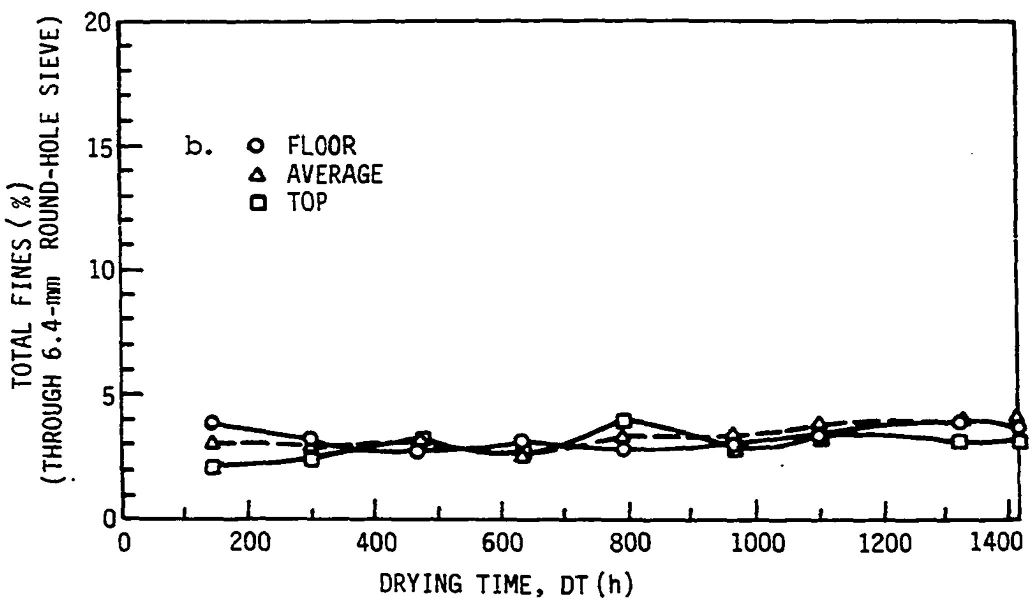
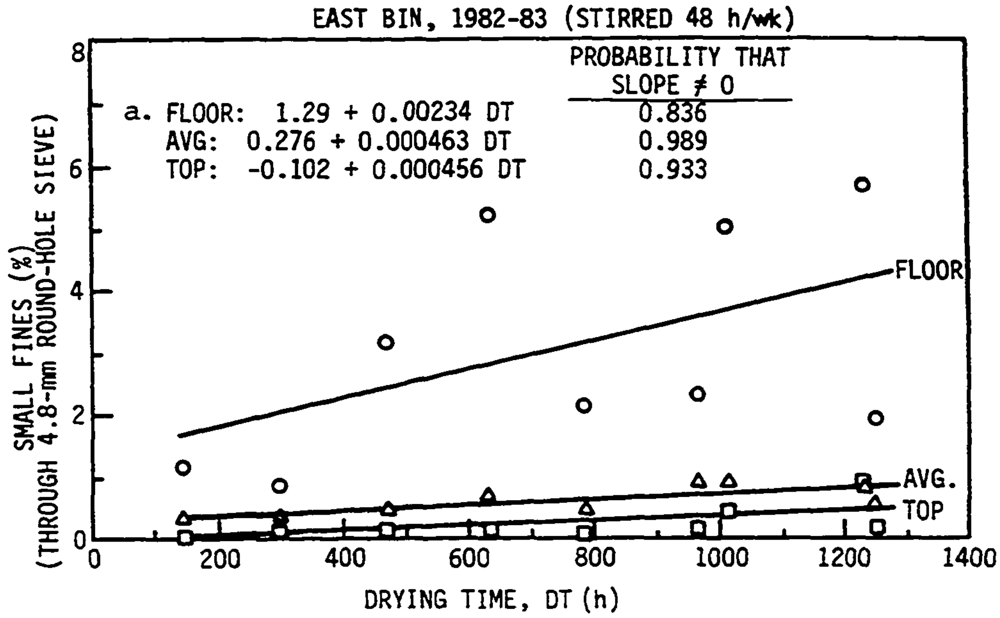


FIGURE 15. Fines distribution in unstirred corn



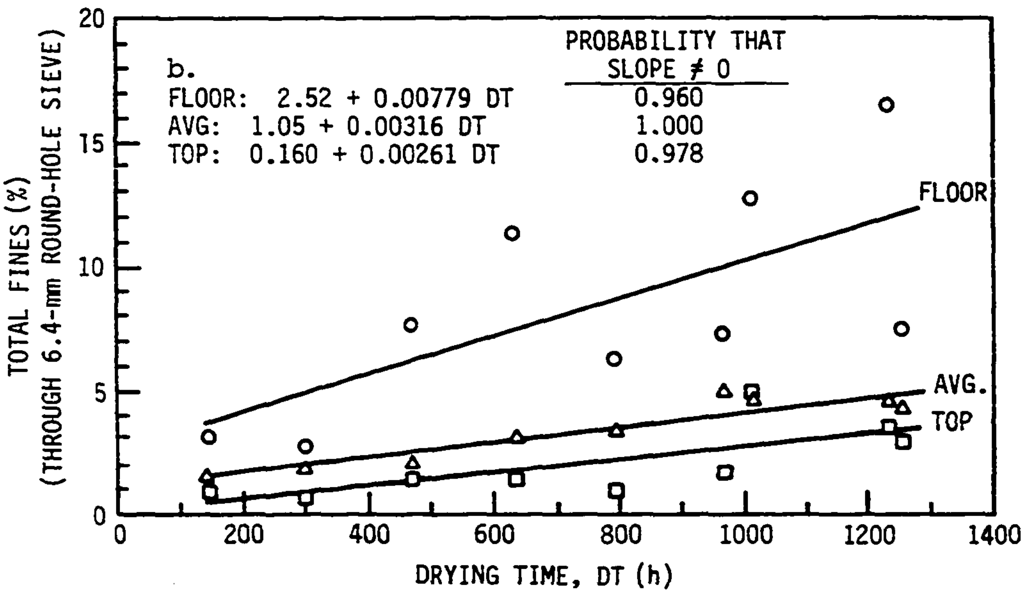


FIGURE 16. Fines distribution in corn stirred weekly

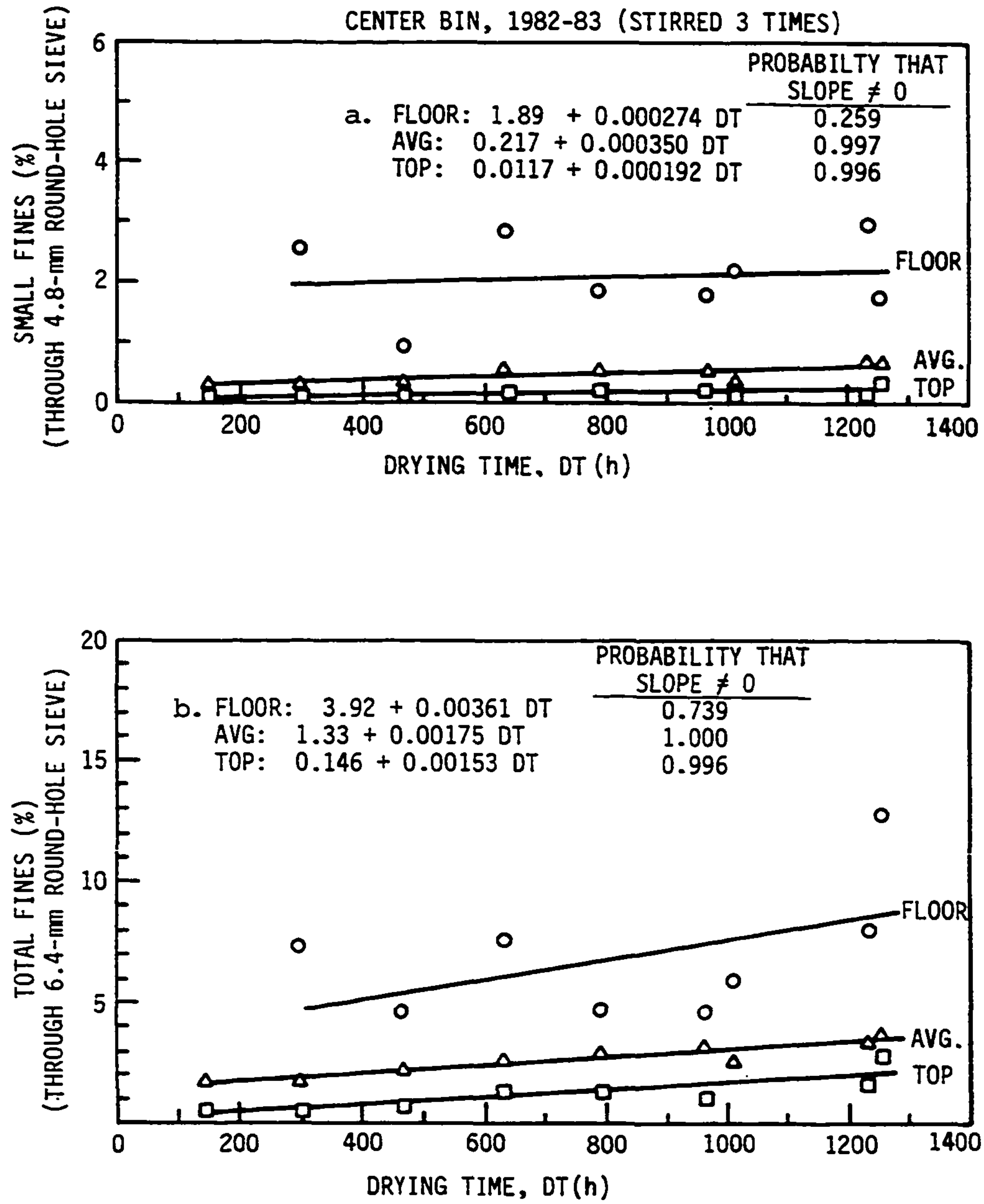


FIGURE 17. Fines distribution in corn stirred three times

Fines data for the stirred bins are plotted in Figures 16 and 17 along with best fit curves produced by linear regression. Floor fines data for both bins were widely scattered and values from the first probe of the center bin were so unreasonable that they were left out of the analysis. The erratic week-to-week variation in floor fines data was probably caused by vacuum-probe characteristics and fluctuations in moisture content of fines on the floor. Hurburgh et al. (1979) found that vacuum samplers draw in a disproportionately large quantity of fines, especially when concentration is high. So during dry weather, the probe probably exaggerated fines content in floor samples. During wet weather, floor fines rewet, became sticky, and tended to crust together. Most likely, fines did not flow into the probe very well and reported fines concentrations are too low under these conditions.

Positive slopes for all lines in Figures 16 and 17 indicate an increase in fines content at all depths during stir drying. Except for Figure 17a, lines for floor concentration have the greatest slope, meaning either more fines were produced near the floor or stirring shifted fines downward. The fact that floor samples were actually taken below the ends of the stirring augers indicates a fines shift.

The wide scatter in floor fines data reduces confidence in the slope values listed in Figures 16 and 17. Except for Figure 16b, the probabilities that the slopes are nonzero are all less than 85%. But observations made during bin unloading added evidence that stirring shifted fines downward. Corn in the bottom third of the stirred bins flowed poorly because of high fines content and corn on the floor below the ends of the stirring augers had extremely high fines content. Many of the fines on the floor had crusted together and were scooped out in chunks.

Grama et al. (1984) developed a set of clean corn multipliers (CCM) quantifying the air flow resistance of mixtures of clean shelled corn and fines. Their CCMs were used to estimate the effect of a fines shift on airflow resistance. It can be shown that, theoretically, airflow resistance should be the same whether fines are uniformly distributed throughout a bin or concentrated at bottom. In practice, crusting of fines on the floor in wet weather may have restricted airflow. Unfortunately, no data were taken that allowed analysis of airflow resistance of the crusted fines.

Brooker et al. (1974) present an equation for pressure drop through perforated floors that shows pressure drop to be inversely proportional to the square of the void fraction of grain above the floor.

$$\Delta P = (10^{-6}/9)(Q/(EO_f))^2$$

where ΔP = pressure drop through floor (in. H_2O)

Q = airflow (cfm/ft^2)

E = void fraction of grain on floor

O_f = open fraction of floor

Using typical values of 20 cfm/ft^2, 10% open floor, and 40% as void fraction for clean grain, ΔP_{floor} = 0.0278 in. H_2O. But if a high concentration of fines cuts void fraction to 20%, pressure drop through the floor increases to 0.111 in. H_2O. This illustrates that fines on the floor can affect total airflow resistance. But void fractions were not measured, so exact calculations are not possible.

Values taken from the floor fines curves in Figure 16 and 17 show that the ratio of small fines to total fines decreases over time. This indicates that large fines accumulated on the floors of the stirred bins slightly faster than small fines. Stirring may have either caused greater movement of large fines or produced more large fines.

Summarizing discussion on fines movement: 1) stirring shifted fines toward the floor, but vacuum-probe samples did not allow accurate quantification of the shift; 2) a concentration of fines on the drying floor may have increased total airflow resistance by crusting together, and by increasing pressure drop through the floor.

<u>Fines production</u> Slopes of lines for average fines concentration in Figures 16 and 17 are positive with a high probability (greater than 98%) of being nonzero. This indicates that stirring increased fines content.

Further evidence of fines production by stirrers was provided by pelican samples taken during bin filling and unloading. Wet corn was sampled as it flowed from wagons into screw conveyors used for bin filling. Dry corn was sampled after it left under-floor bin unloading augers. Any increase in fines between these two sampling points is attributable to damage from fill and unload augers, grain spreaders, kernel stresses caused by temperature and moisture gradients during drying, insects, and stirring. No insects were found during drying, so insect damage was considered negligible. Handling equipment and drying stresses were similar for all three bins, so fines production from these factors was assumed to be the same in each bin and was assumed to be represented by fines increase in the unstirred bin. Subtracting fines increase in the unstirred bin from fines increase in the stirred bins should give an estimate of fines production from stirring.

Table 4 shows the fines increases in all three bins in 1982-83. No increase in BCFM was measured in the unstirred bin and large fines increased only 1.10 percentage points or about 556 kg on a dry matter basis. Net increase in fines from stirring (in kg dry matter) was similar for the two stirred bins. But because the center stirrer operated less than half as many hours as the east one, fines production per hour of stirrer operation was more than twice as high in the center bin. It's possible that some characteristic of the center stirrer caused greater grain damage. A more likely explanation though, is that rate of fines production decreases with time. Stirrers probably break kernels that were cracked by the combine, fill auger, and spreader. Once cracked kernels are broken, only sound kernels remain and rate of fines production decreases. This would give lower dry kg fines production per hour for stirrers operated longer. Figure 18 supports the argument. Fines production in the east bin was nearly a linear function of stirring time for 300 h, but then leveled off.

Fines production rates in Figure 18 not only leveled off, they turned negative. This is unreasonable because it implies that fines content in the bin decreased. The apparent decrease in fines was probably caused by the vacuum-probe problem described earlier. After 300 h of stirring, many of the fines had shifted to the drying floor and crusted together, inhibiting flow into the probe. Poor probe sampling also caused discrepancies between values in Figure 18 and values from pelican samples in Table 4.

TABLE 4. Fines production from stirring corn[a]

	East[b]			Center[c]		
	BCFM[e]	LF[f]	Total	BCFM	LF	Total
Final						
%	1.70	3.70	5.40	1.50	3.70	5.20
dry kg	1062	2311	3373	933	2301	3234
Initial						
%	1.00	2.20	3.20	0.92	2.10	3.02
dry kg	625	1374	1999	572	1306	1878
Increase						
dry kg	437	937	1374	361	995	1356
Net increase[g]						
dry kg	437	381	818	361	439	800
dry kg/h	1.06	0.92	1.98	2.36	2.87	5.23

[a] Data from pelican samples taken 1982-83; 1 stirring auger per bin, 513 r/min axial rotational speed, 4.2 m/h horizontal speed.

[b] Stirred 48 h/wk, 414 h total; 4.22 m average corn depth.

[c] Stirred 3 times, 153 h total; 4.12 m average corn depth.

[d] Unstirred.

[e] Broken corn and foreign material: material through 4.8-mm round-hole sieve plus non-corn material larger than 4.8 mm.

[f] Large fines: material between 6.4-mm and 4.8-mm round-hole sieves.

[g] Net increase from stirring = Fines increase in stirred bin - fines increase in unstirred bin.

	West[d]	
BCFM	LF	Total
1.10	3.20	4.30
680	1978	2658
1.10	2.30	3.40
680	1422	2102
0	556	556
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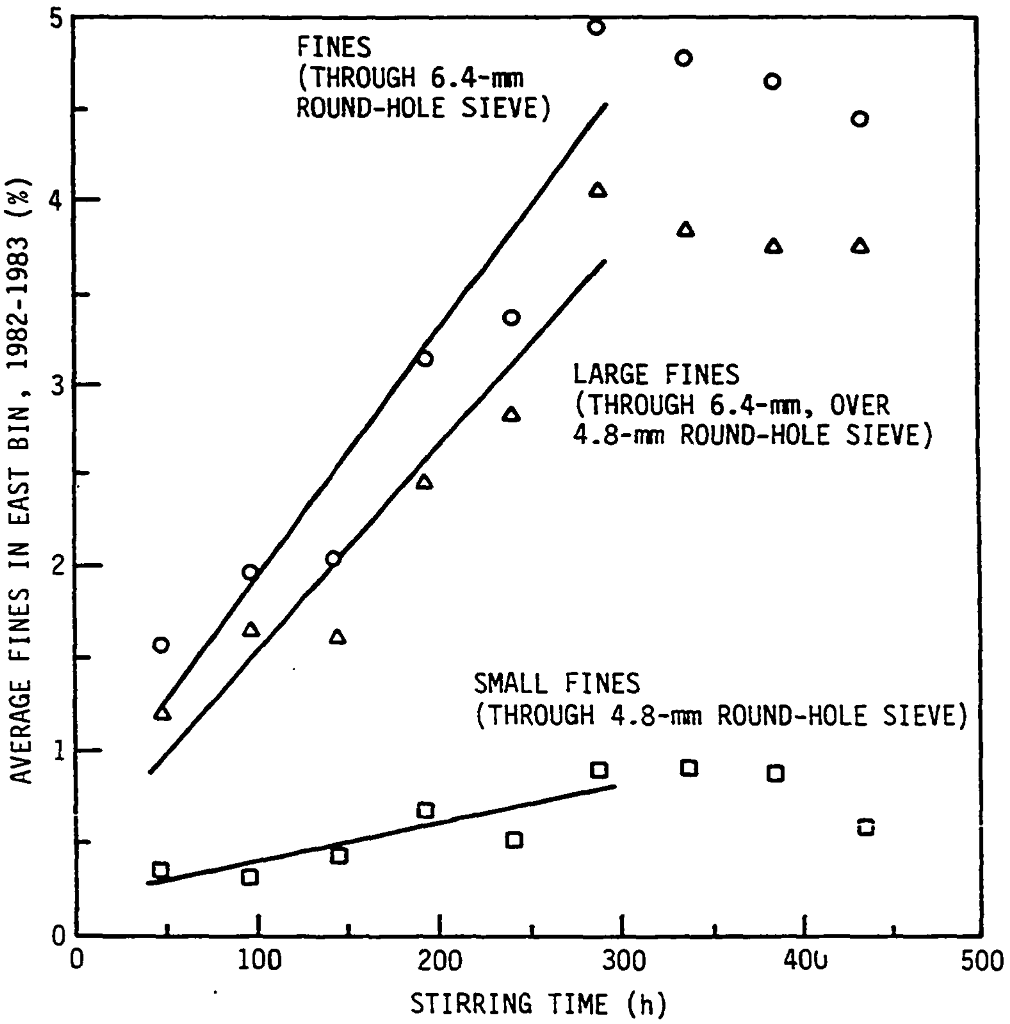

FIGURE 18. Fines production indicated by probe samples

Initial fines concentrations were very uniform for incoming loads of wet corn. But because stirring shifted fines toward bin bottom, fines concentration was much higher for the last loads of dry corn removed from the bins. As workers scooped out the last corn, fines flow became erratic and difficult to sample accurately. In 1982-83, a surge wagon was used in an attempt to even fines flow and improve sampling accuracy. Using a surge wagon must have helped, because it was not used in 1983-84 and fines data were so erratic that they were unusable.

Uneven fines flow from stirred bins could cause market discounts when loads are valued individually. Average BCFM in the stirred bins was well below the 3% discount level, but a few loads exceeded 3%. In 1982-83, the last load from the east bin contained 5.4% BCFM and the last two loads from the center bin contained 3.7% and 3.2%, respectively. No premiums are given for low BCFM, so several loads with excess BCFM would reduce profit. If properties for all loads from a bin are averaged however, stirring should not cause BCFM discounts.

Using clean corn multipliers from Grama et al. (1984), the extra fines in the stirred bins should have made SCM about 2% greater than in the unstirred bin by season's end. But SCM was lower in the stirred bins. Evidently effects from bulk density, kernel orientation, and moisture changes offset the effect of fines increase.

Table 4 shows that stirring produced roughly equal quantities of small and large fines. When fines production from drying stress and handling is added in however, large fines production exceeds small fines by more than 2 to 1 in stirred bins. Thus, the greater accumulation of large fines than small fines on the floors of the stirred bins was probably due to an abundance of large fines rather than selective movement by the stirrers.

Drying results

Drying time, energy use, and final moisture contents for the field tests are given in Table 5.

1982-83 results Because the stirred bins had higher airflow and fans could be shut off when average moisture fell below 15.5%, they dried about 11% faster and used about 10% less electric energy than the unstirred bin. Stirring equipment used little electric energy--4.9% of the total for weekly stirring and only 1.4% for three-time stirring. The east fan motor was slightly less efficient than the center one and so used more energy for the same drying time.

Drying energy index (DEI) expresses electric-energy use per unit of water removed from the corn. It is the ratio of energy purchased for grain drying to the heat of

TABLE 5. Field test drying results

	1983-84 East[a]	Center[b]	West[c]
Corn quantity, t[e]	78.57	77.80	79.20
Fan motor power			
nominal output, hp	3	5-7	5-7
measured input, kW	3.26	6.45	6.39
Initial airflow, L/s•t	24.3	37.7	29.5
Stirrer power			
measured input, kW	1.03	0.78	--
Moisture content			
initial, % wet basis	19.54	19.60	19.72
final, % wet basis	15.37	15.18	14.32
Drying time, h	968	675	936
Purchased drying energy			
fan, kWh	3159	4349	5984
stirrer, kWh	91	105	--
total, kWh	3250	4454	5984
kWh/t	41.36	57.25	75.56
kWh/t•%	9.92	12.95	13.99
DEI[f]	1.17	1.53	1.67

[a]Stirred twice.

[b]Stirred 3 times.

[c]Unstirred.

[d]Stirred 48 h/week.

[e]1 t = 1000 kg corn @ 15.5% moisture (wet basis) = 845 kg dry matter = 39.37 bushels.

[f]Drying energy index = (purchased energy/mass water removed)/ (heat of vaporization of free water @ 20 C).

	1982-83	
East[d]	Center[d]	West[c]
73.92	73.61	73.16
5-7	5-7	5-7
6.61	6.49	6.49
38.3	38.3	27.5
1.03	0.77	--
24.73	24.61	24.66
14.10	13.65	13.02
1254	1254	1416
8292	8137	9187
426	118	--
----	----	----
8718	8255	9187
117.9	112.1	125.6
11.09	10.23	10.79
1.25	1.16	1.23

vaporization of free water at 20 C. Because DEI is dimensionless, it allows convenient comparison of dryer performance regardless of fuel type or system of units. Three-time stirring gave the best (lowest) DEI. Even though the unstirred dryer used the most electricity, it also removed the most water and had second best DEI.

The unstirred dryer removed more water than desired--it overdried corn 2.48 percentage points (15.5%-13.02%). Some overdrying occurred in the stirred dryers, too--1.4 points for weekly stirring and 1.85 points for three-time stirring. Overdrying in the stirred bins could have been reduced by sampling corn more frequently as drying neared completion and by processing the samples faster. Overdrying was unavoidable in the unstirred bin because bottom layers were well below 15.5% moisture by the time the top layer dried to 15.5%.

No visible spoilage occurred in any of the bins.

1983-84 results   Because three-time stirring used less electric energy than weekly stirring in 1982-83, weekly stirring was abandoned in 1983-84. Instead, the east bin was operated on the same stirring plan as the center bin, but with a smaller fan.

Stirring made initial airflow in the center bin 28% greater than in the unstirred bin with the same size fan.

Stirring also allowed the small east fan to deliver almost as much air as the west one with about half the power input. Having highest airflow, the center bin dried fastest. Even though the east bin took longest to dry, its low power input resulted in lowest total energy use and lowest DEI. The center bin had next best DEI. Stirring used 2.8% of total electric energy for the east bin and 2.4% for the center bin. Poor drying weather made energy use for all three bins higher than normal.

With more frequent sampling and slower drying due to poorer weather, less overdrying occurred in 1983-84--0.13 percentage points in the east bin, 0.32 points in the center, and 1.18 points in the unstirred bin.

Again, no visible spoilage occurred in any of the bins.

Summary

In field tests comparing stirred and unstirred natural-air corn dryers, stirring wet, spreader-placed corn initially cut airflow resistance 30 to 50% and increased airflow 28 to 41%. Repeated stirring, however, tended to increase airflow resistance and reduce airflow from initial levels. In unstirred bins, airflow resistance decreased and airflow increased as corn dried. Equations were developed relating changes in airflow and airflow resistance to percentage points of moisture removed.

Because airflow resistance is a function of grain porosity, which in turn is a function of bulk density, bulk density was measured in the field tests. Bulk density decreased as unstirred corn dried. This may explain the decrease in airflow resistance. Initial stirring decreased bulk density about 5% and partially explains large decreases in airflow resistance of stirred corn. But subsequent stirrings produced unpredictable bulk density changes that did not fully explain airflow resistance changes. Kernel orientation may have influenced airflow resistance of stirred corn, but it was not studied in these field tests.

Stirring during bin filling was found to have the same effect on airflow as stirring after filling. Because starting stirring augers in a full bin of wet corn is difficult, can be dangerous, and can damage stirring equipment, stirring during bin filling is recommended.

Stirring produced an average of about 1.7 kg dry matter BCFM per hour of stirring. This rate of fines production should not lead to market discounts when properties of all loads are averaged.

A layer of fines developed on the floor of the stirred bins below the ends of the stirring augers and formed a crust during wet weather. Both the fines increase and fines layer on the floor help explain the increase in airflow resistance with repeated stirring.

Both weekly and three-time stirring reduced drying time, electric energy use, and overdrying in natural-air corn dryers. Stirring also allowed successful drying of 20% moisture corn with a smaller fan, which resulted in considerable energy savings.

COMPUTER SIMULATION

The field studies showed that, under the conditions tested, stirring improved performance of natural-air dryers. But can we expect the same results under different weather conditions, with different airflows, or for other harvest moistures and dates? What are the airflow limits before spoilage occurs? What average energy use and final moisture content can we expect with and without stirring?

Using field tests to answer these questions would be very slow and expensive. Fortunately, mathematical models have been developed that allow simulation of natural-air corn drying using a computer. Computer models provide very rapid "testing" of many different dryer designs under controlled weather conditions at relatively low cost. Brooker et al. (1974), Morey et al. (1978b), Van Ee (1980), and Fon (1983) describe some of the models that are available.

To study natural-air stir drying under conditions different from those in the field study, I developed a computer model called NADWIS (natural air drying with stirring). Field test results were used to calibrate and validate the model. After the model appeared to be giving suitably accurate results, it was used to simulate drying corn of various moisture contents harvested mid-October in central Iowa.

Model Description

NADWIS is a modified version of FALDRY--a low-temperature drying model developed at Iowa State University by Van Ee (1980). FALDRY is based on Morey's model (Morey et al., 1976, 1977), which had its roots in Thompson's storage model (Thompson, 1972). I selected FALDRY because it has been validated against field test results by both Morey and Van Ee, it was available on the Iowa State University computer system, and I already had some experience using the model.

FALDRY allows simulation of layer-filled bins and contains subroutines that recalculate grain depth (FILL) and airflow (FAN) each time grain is added. FAN contains some empirical equations that give fan airflow as a function of motor horsepower. In my field studies, airflow was found to be a function of average corn moisture, so FAN was replaced with equations from Figures 6, 8, and 10. After each simulated day of drying, NADWIS calculates points of moisture removed since bin filling (PR) and uses the value in the appropriate airflow equation to calculate a new airflow for the next day of drying. NADWIS was intended only for single-fill drying, so the FILL subroutine was deleted. To simulate stirring, a subroutine was added that sets grain temperature, wet basis moisture, and accumulated dry matter decomposition for each layer equal to the bin average at the end of days on which stirring is called for.

A flowchart for NADWIS is shown in Figure 19 and a FORTRAN listing of the program and a sample output are in Appendix B. Changes made to FALDRY to develop NADWIS are summarized in the section on model validation.

Here are the inputs needed to run NADWIS. U.S. customary units are employed because FALDRY and its parent programs were written using these units.

- Number of bins to be simulated (1 to 6 allowed).
- Bin diameter (ft).
- Electrical power drawn by fan motor (kW). If better information is lacking, assume 1 kW input/hp output.
- Initial airflow (cfm/bu) after bin is full and first stirring is complete.
- Stirring option:

  -2.0: no stirring, constant airflow.

  -1.0: one initial stirring with constant airflow (user should input higher airflow than for option -2.0).

  0.0: no stirring, airflow varies as in Figure 6.

  1.0: two or three time stirring (at beginning and end of drying and when wet basis moisture of corn

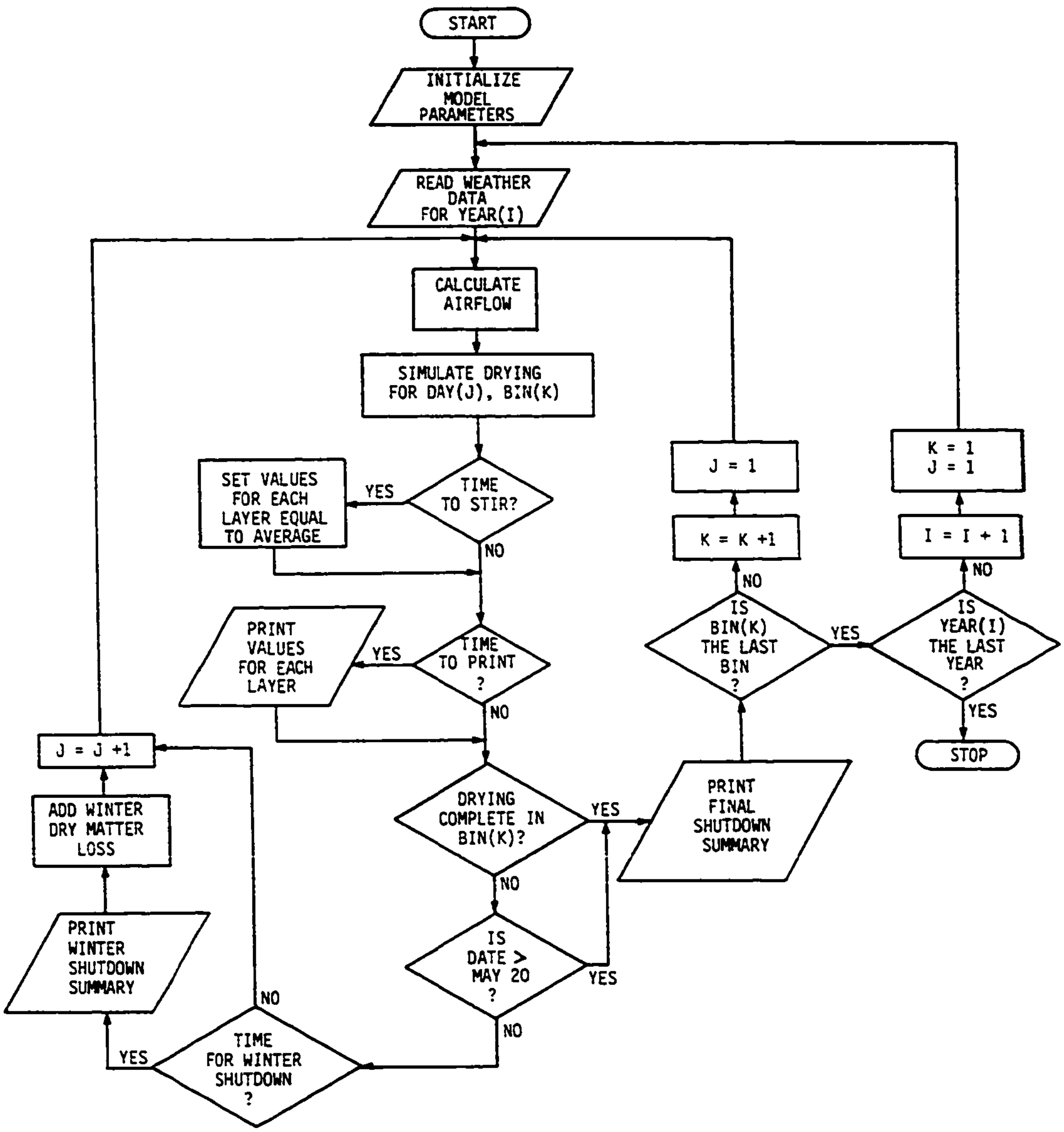

FIGURE 19. NADWIS flowchart

wetter than 21% falls below 20%), airflow varies as in Figure 10.

2.0: weekly stirring (at beginning and end of drying and every 7 days during drying), airflow varies as in Figure 8.

- Amount of supplemental heat, in either degrees F or Btu/min, beyond heat provided by fan motor and impeller.
- Print option. User can obtain hard copy of current conditions in each layer daily, weekly, every 2 weeks, or at shutdown, plus average conditions at shutdown, or just average shutdown conditions.
- Final maximum moisture (% wet basis). Drying simulation continues until moisture of wettest layer is less than value specified, or date is May 20.
- Final average moisture (% wet basis). If maximum moisture criterion is met, drying simulation stops when average moisture is less than value specified or date is May 20.
- Number of layers to be simulated in each bin (1 to 20 allowed, 10 recommended). A greater number of layers increases accuracy, but also increases computer time and cost per run.

- Harvest date (1 = September 7 to 100 = December 16), initial corn moisture (% wet basis), initial corn temperature (F), and corn quantity (dry matter bushels).
- Weather data. I obtained a magnetic computer tape of hourly (in some years three-hourly) weather records for Des Moines, Iowa, 1945 through 1983, from the National Climatic Data Center in Asheville, North Carolina. I then wrote computer programs to read spring and fall data, 1963 through 1983, calculate daily averages for dry bulb temperature, relative humidity, and absolute humidity, and store the averages on disk. NADWIS read the average weather values from disk.

Model Validation

Accuracy of NADWIS was checked by comparing simulation results with field test results for fall 1982. The first version of NADWIS used 100% of input airflow in the drying simulation and used 100% of electric power input to the fan motor to calculate temperature rise of drying air. (Only positive-pressure, axial-flow fans were considered.) NADWIS badly overpredicted drying, especially in lower layers (Figures 20, 21, and 22).

Morey et al. (1977) and Anderson[4] experienced similar problems when trying to validate their respective versions of the Thompson storage model. Anderson found that at a given static pressure, not all airflow read from the manufacturer's fan performance curve was really available for drying. He applied a "system loss" factor of 0.7442 to reduce airflow used in simulation. Morey et al. (1977) found that airflow is not evenly distributed across the diameter of natural-air dryers. They used correction factors of 0.73 to 0.81 to reduce simulation airflow to allow for uneven drying. An airflow effectiveness factor of 0.74 improved agreement with field test results (Figure 23), but NADWIS still overpredicted drying.

Morey et al. (1977) calculated plenum temperature rise using 57.5% of fan electrical power. They assumed 85% motor efficiency and 50% impeller efficiency. The remaining 42.5% of input power was assumed to be dissipated through the corn mass and was used to calculate a small temperature rise in each layer. For NADWIS, best results were obtained by using 57.5% of electrical power to calculate plenum temperature rise and ignoring the rest (Figures 24, 25, and 26).

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[4] Personal communication with Michael E. Anderson, research associate, Iowa State University Agricultural Engineering Department.

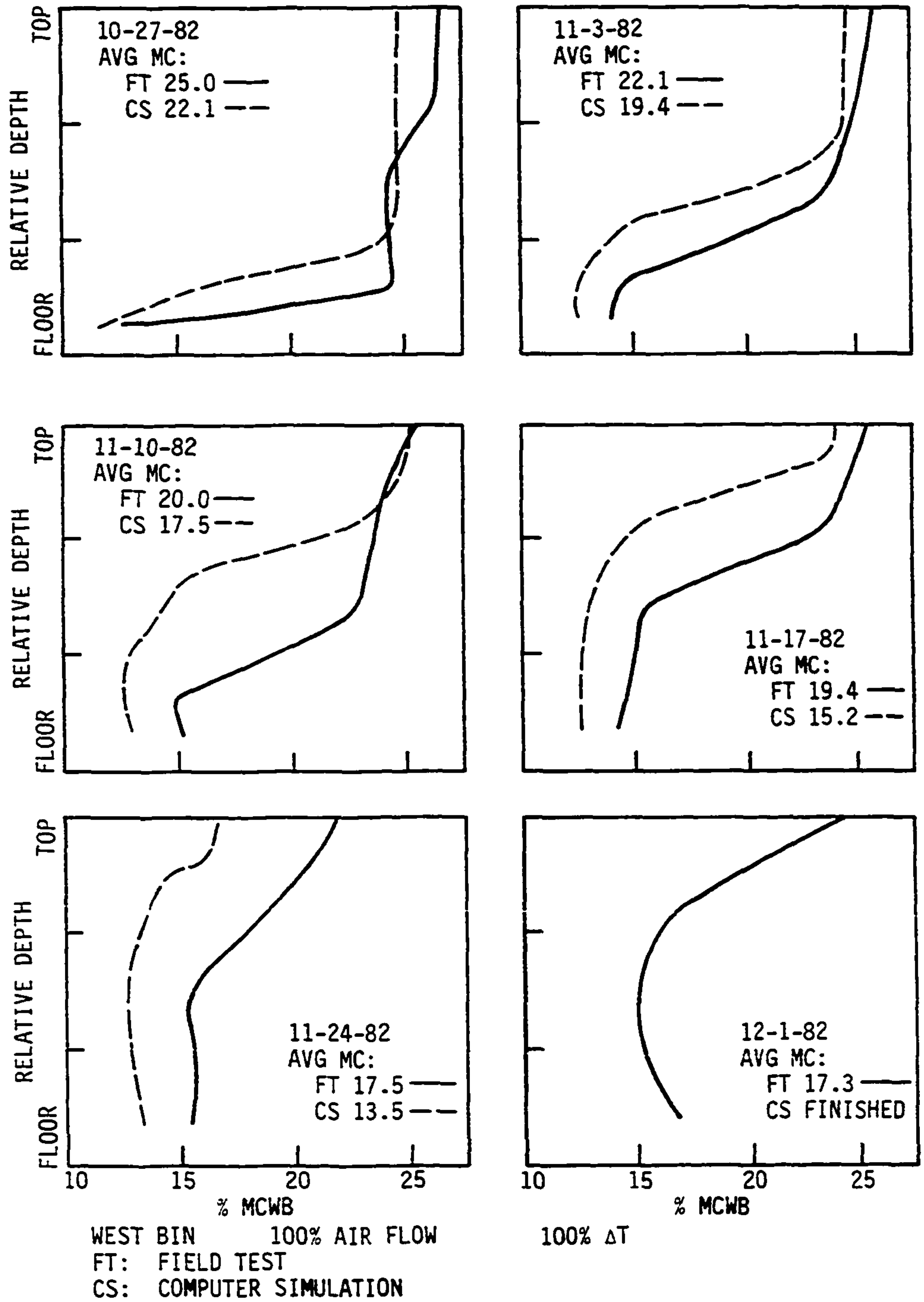

FIGURE 20. Simulation results for unstirred corn, 100% airflow, 100% temperature rise

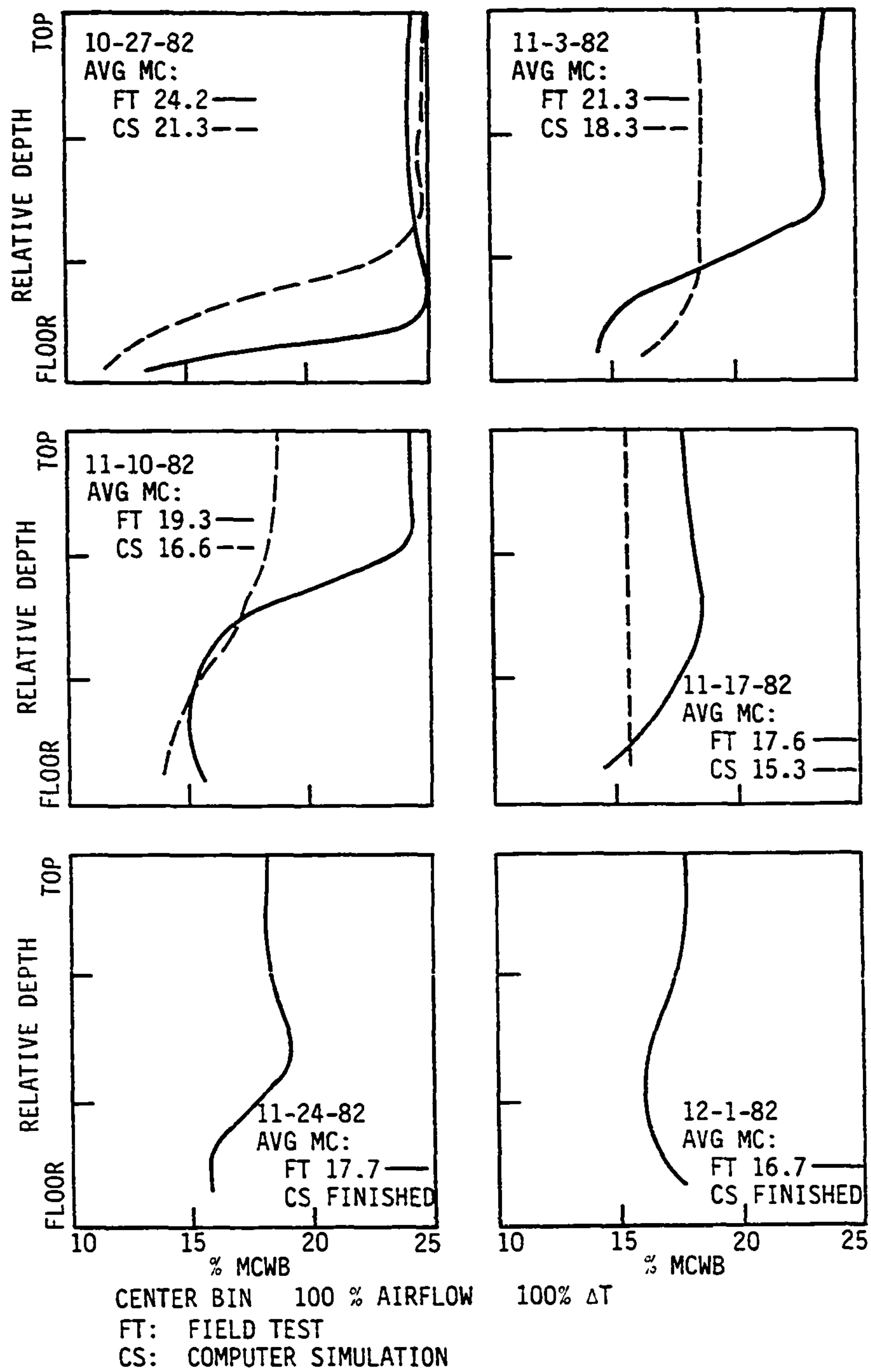

FIGURE 21. Simulation results for corn stirred three times, 100% airflow, 100% temperature rise

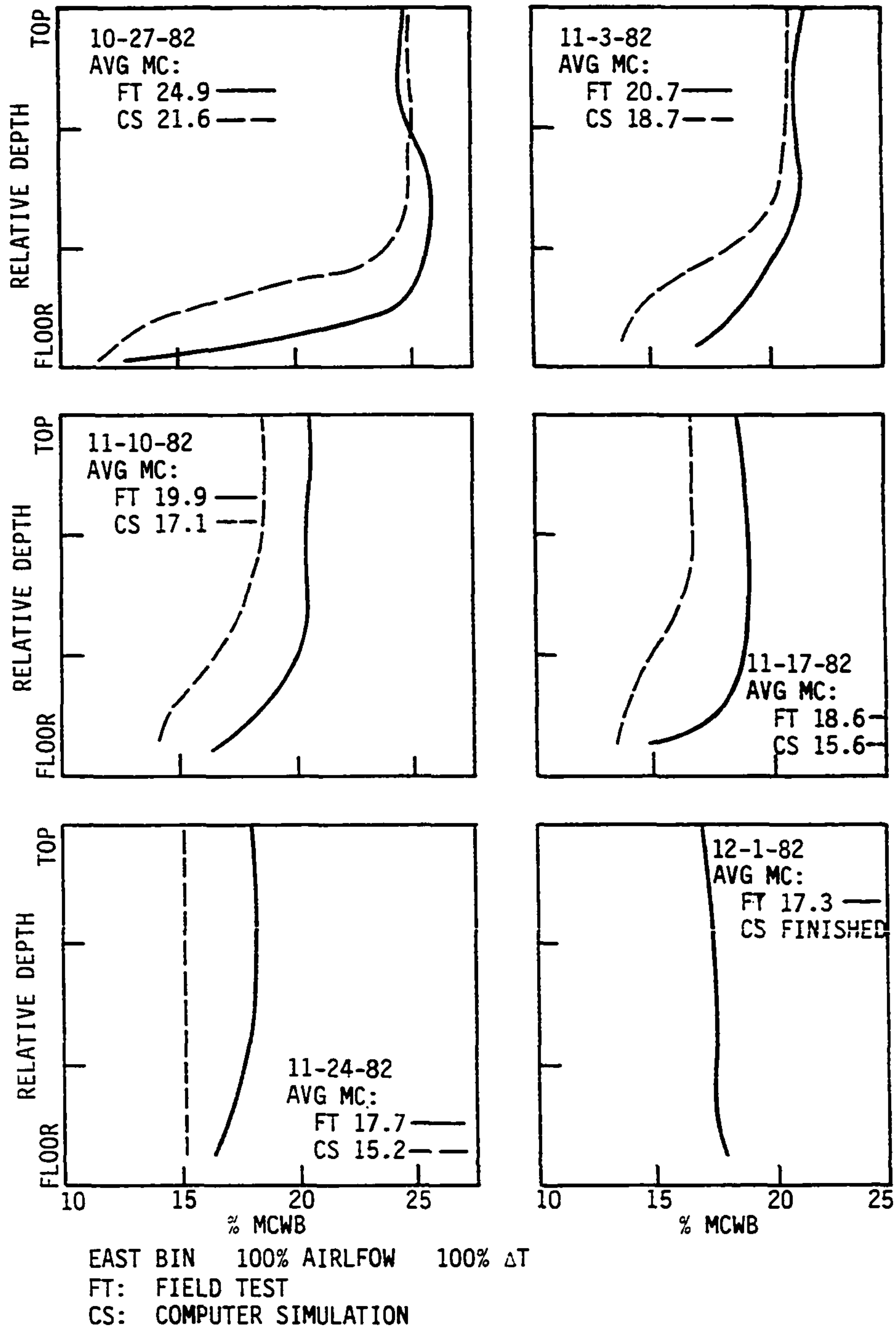

FIGURE 22. Simulation results for corn stirred weekly, 100% airflow, 100% temperature rise

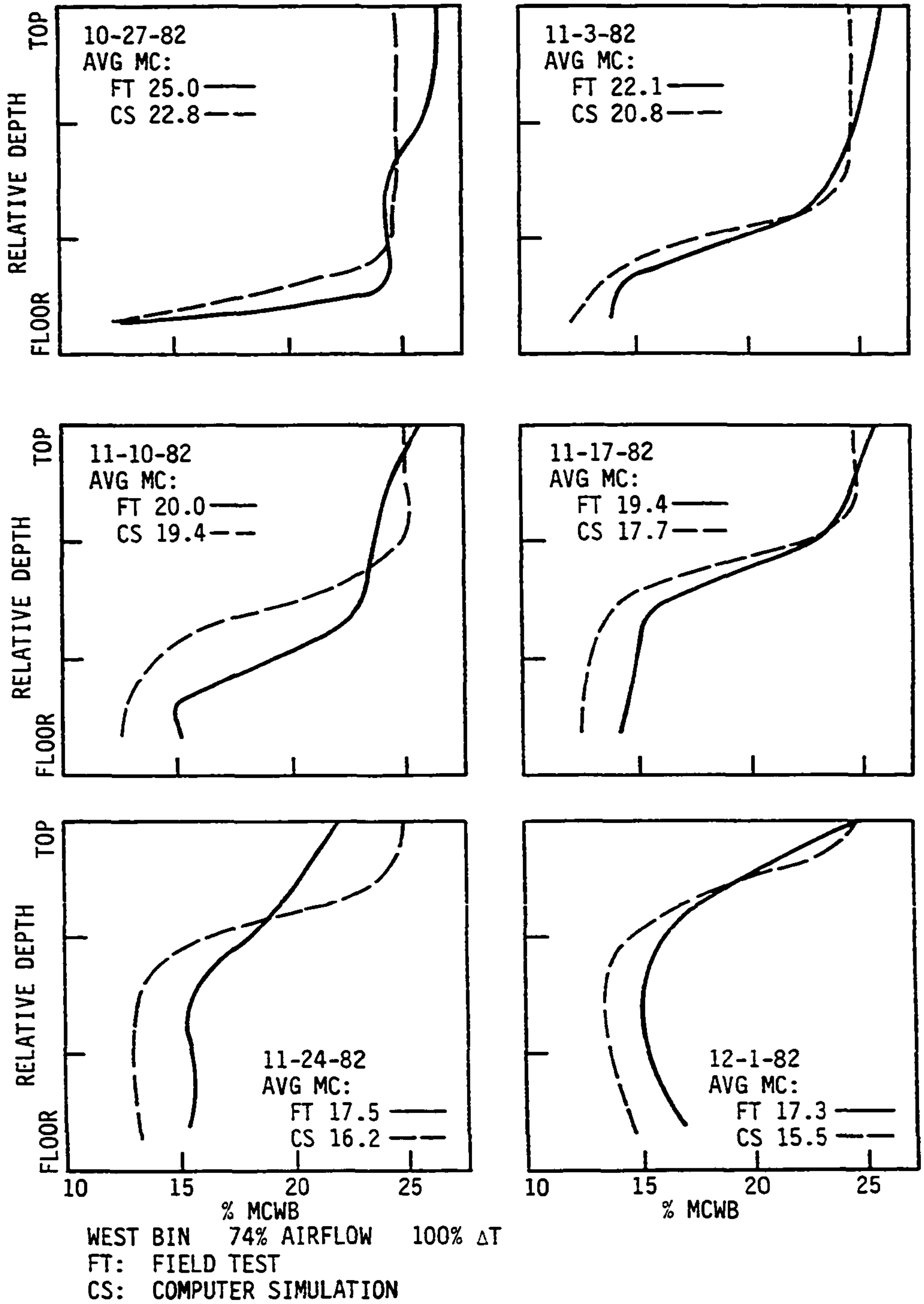

FIGURE 23. Simulation results for unstirred corn, 74% airflow, 100% temperature rise

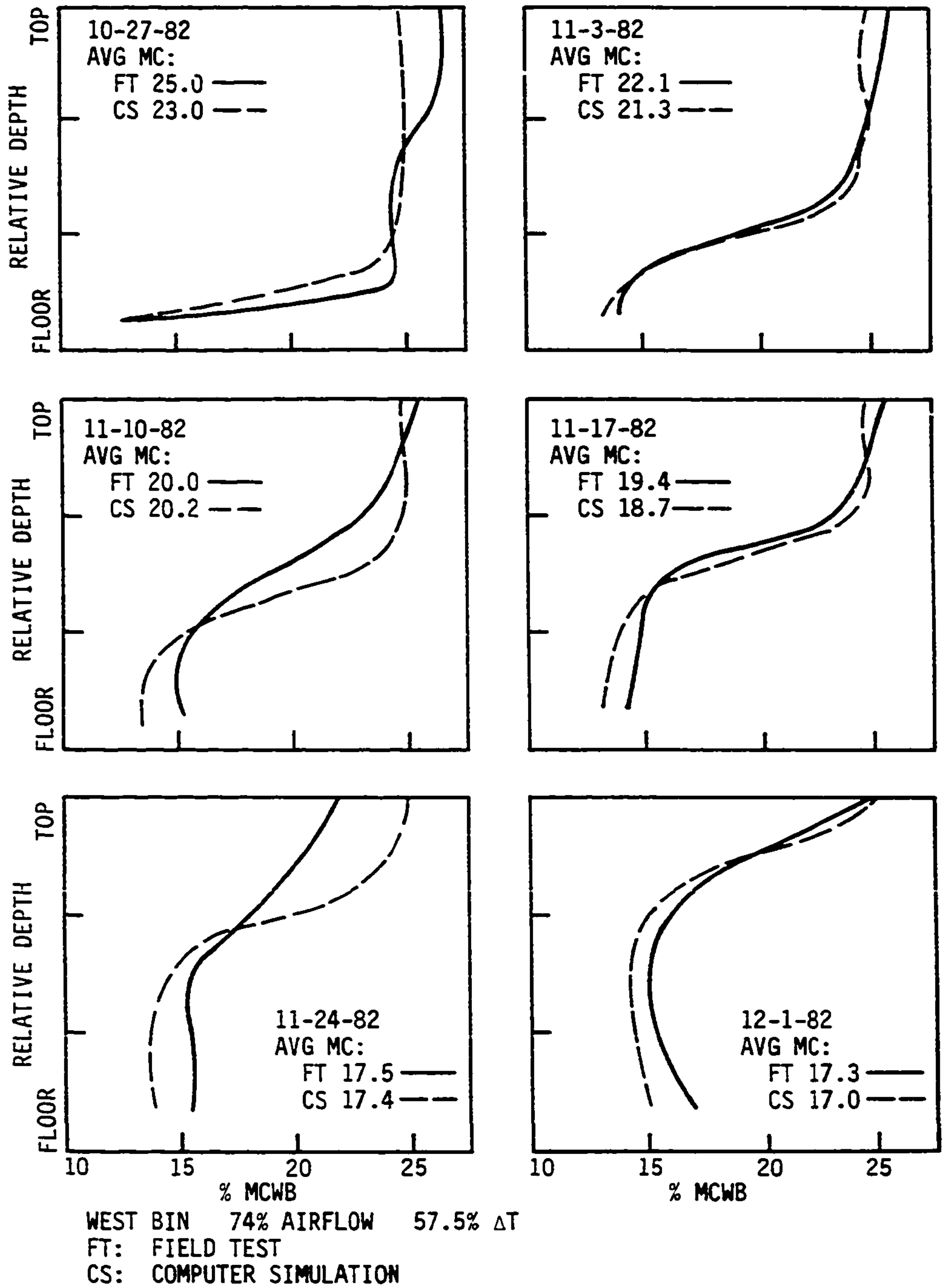

FIGURE 24. Simulation results for unstirred corn, 74% airflow, 57.5% temperature rise

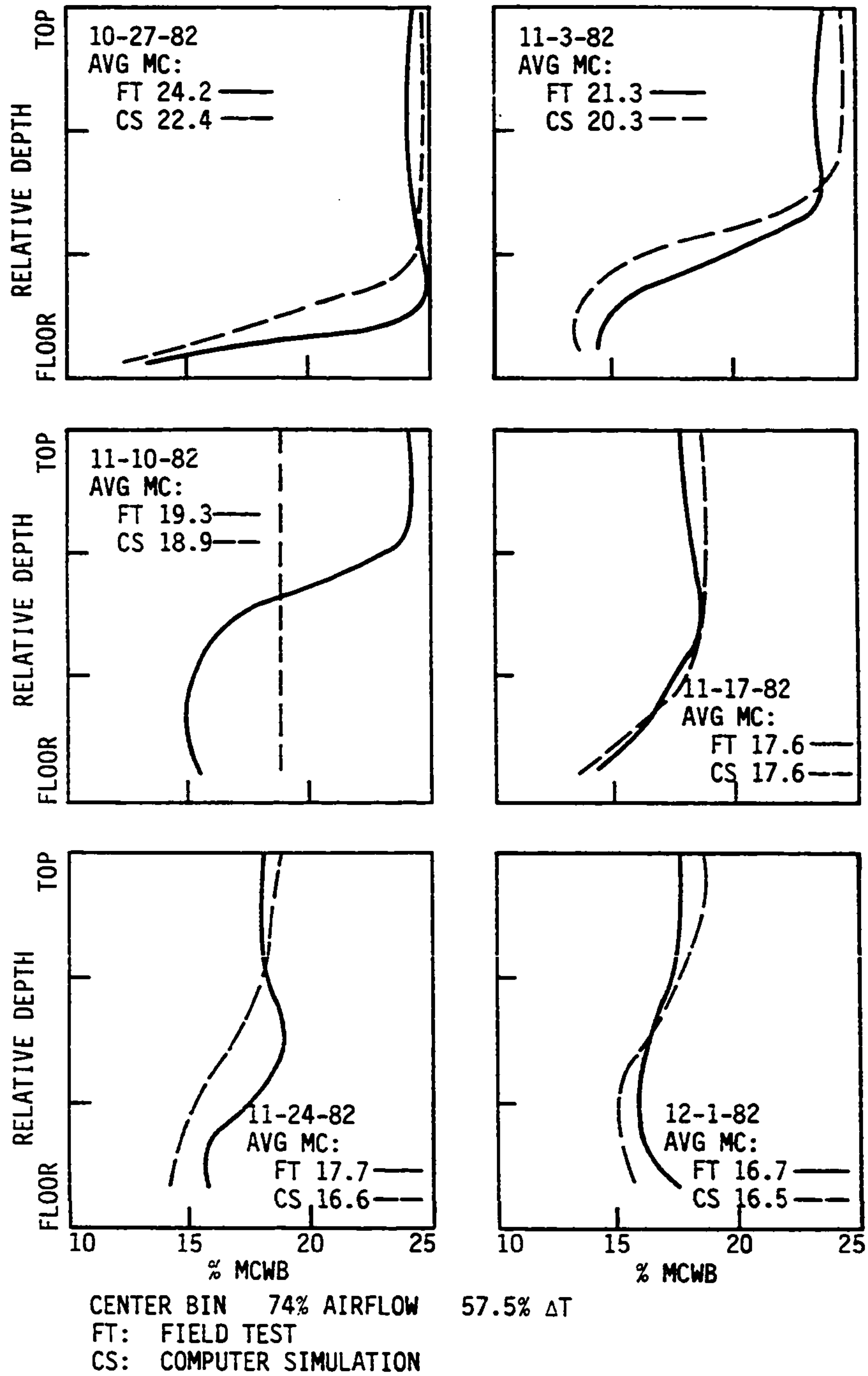

FIGURE 25. Simulation results for corn stirred three times, 74% airflow, 57.5% temperature rise

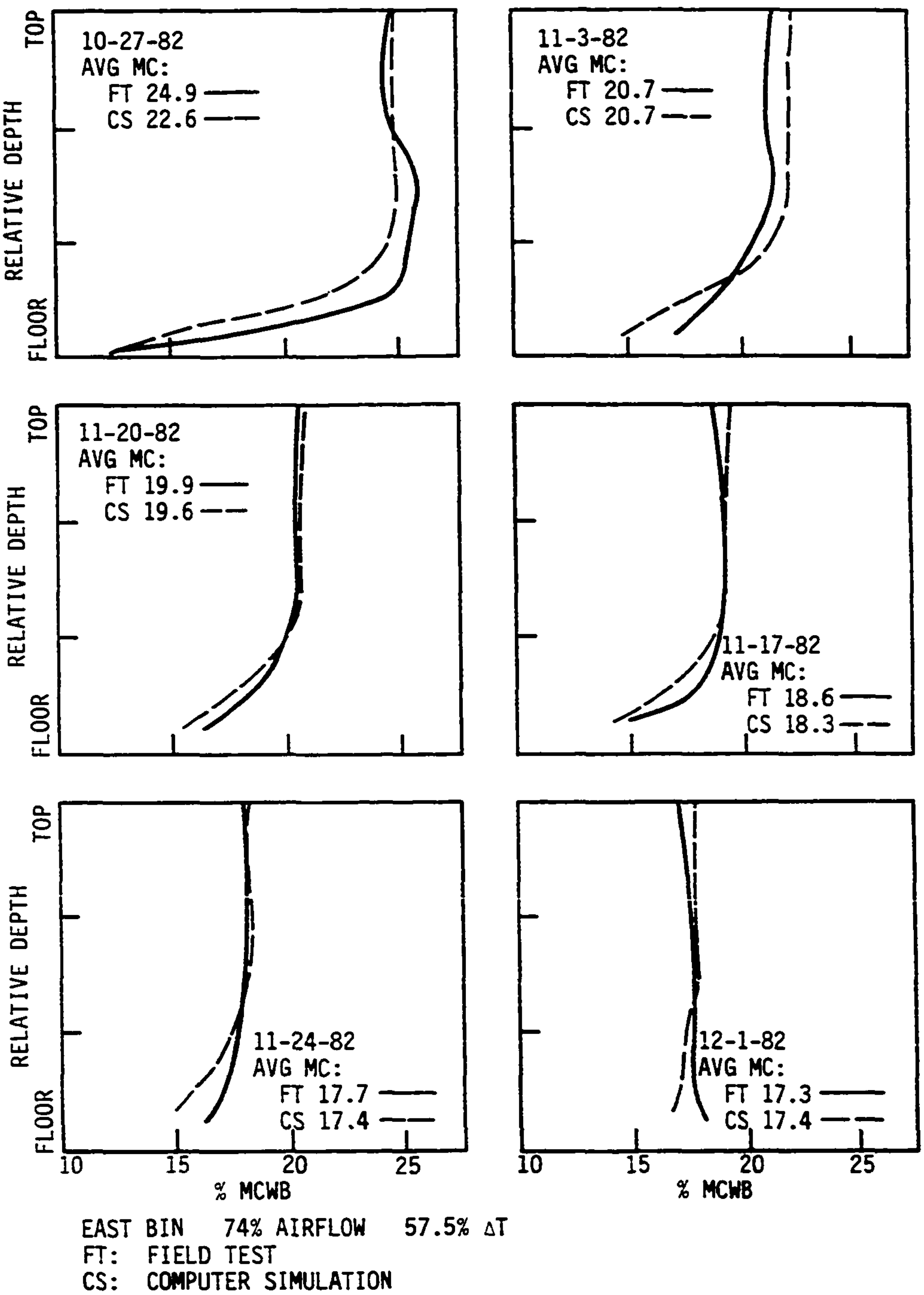

FIGURE 26. Simulation results for corn stirred weekly, 74% airflow, 57.5% temperature rise

Discrepancies between simulation results and field test results in Figures 24 to 26 can probably be explained by these factors:

- Field tests were conducted near Ames while weather data for simulation are from the Des Moines airport (65 km away).
- Equilibrium moisture and drying equations used in the model were probably developed for corn varieties different from those used in my field tests.
- Inaccuracies in instruments and techniques undoubtedly caused some measurement errors of corn depth and moisture and airflow in the field studies.

For this study, average bin moistures are more important than moisture profiles. Figures 24, 25, and 26 indicate good agreement between average moistures, so accuracy of this version of NADWIS was considered acceptable.

Here is a summary of changes made to FALDRY in the development of NADWIS.

- AVGWTH, a subroutine that allows drying simulation with long-term average weather rather than daily values, was eliminated.

- OPTDRY, a subroutine that uses an optimized layer-filling technique, was eliminated.
- FILL and MSTPRF, layer-filling subroutines, were eliminated.
- FAN was replaced with airflow equations from my field tests. The appropriate airflow equation (in subroutine VANCE) is determined by the stirring option selected.
- STIR, a subroutine to simulate stirring, was added.
- A factor of 0.74 was inserted into an equation in subroutine VANCE to reduce the effective airflow used in simulation.
- A factor 0.575 was inserted to reduce temperature rise calculated in subroutine VANCE.
- Some additional statements were added to the shutdown logic in subroutine VANCE to call for stirring.

Variable Selection

I selected model input variables to simulate, as accurately as possible, typical corn harvest and drying conditions in central Iowa. Data from field tests were used when corn physical properties and airflow resistance values were needed.

- Bin diameter: 18 ft (5.5 m) was used to match the diameter of the field-test bins.
- Fan input power: Electric power input to the fan motor was estimated with this formula:

$$\text{Power (kW)} = \frac{(\text{cfm})(\text{SP})(0.746)}{6356\ (0.85)(0.50)}$$

where cfm = total initial airflow through corn (cfm)

SP = initial plenum static pressure (in. H_2O); estimated from initial airflow and SCM from my field tests

0.746 = horsepower to kilowatt conversion factor

6356 = constant

0.85 = assumed motor efficiency

0.50 = assumed impeller efficiency

Examination of performance data for several fans revealed that input power was fairly constant over the normal airflow and pressure operating range. Thus, fan input power was assumed constant throughout drying.

- Initial airflow: Initial airflow was entered in cfm/bu and usually changed in 0.1 cfm/bu increments between runs. The computer model recalculated airflow after each day of drying using airflow equations from Figures 6, 8, and 10. It was assumed that a series of fans of different size with parallel performance curves was available. In fact, at least one manufacturer does sell axial-flow fans from 1.5-hp, 18-in. diameter up through 10-hp, 28-in. diameter with performance curves that are nearly parallel to one another and to those of the field-test fans.

- Supplemental heat: Only natural-air drying was considered, so supplemental heat inputs were zero in all runs.
- Desired final average and maximum moisture: The usual market moisture of 15.5% (wet basis) was used for both variables in all runs.
- Layers modeled: I used 10 layers for all simulations.
- Harvest date: October 15 was used because it is close to actual field-test harvest dates and is typical for central Iowa.
- Corn quantity: Initial bin capacity in bushels was calculated using selected bin depth and diameter and bulk densities measured in field tests. It was assumed that corn producers would fill bins to maximum depth--to the eave in unstirred bins and to within 2.0 ft (0.61 m) of the eave in stirred bins. Typical farm drying bins are 7 rings high.

  Corn depth in unstirred bins (20% MCWB)

  $$= \frac{(7 \text{ rings})\ (32 \text{ in./ring})}{12 \text{ in./ft}} - 1.5 \text{ ft plenum height}$$

  $= 17.2$ ft (5.2 m)

  Corn depth in stirred bins (20% and 24% MCWB)

= 17.2 ft - 2.0 ft stirrer clearance

= 15.2 ft (4.6 m)

With wet corn (MCWB ≥ 24%), fan power requirements become unreasonable in deep, unstirred drying bins. To keep fan power more reasonable, 5-ring bins were assumed for 24% unstirred corn.

Corn depth in unstirred bins (24% MCWB)

$$= \frac{(5 \text{ rings})(32 \text{ in./ring})}{12 \text{ in./ft}} - 1.5 \text{ ft plenum}$$

= 11.8 ft (3.6 m)

- Initial moisture: Drying of 24% MCWB corn was simulated because that value is near harvest moisture in one of the field tests and because 24% is near the upper, practical limit for natural-air drying of single-fill bins. Drying of 20% MCWB corn was also simulated. The second field-test used approximately 20% moisture corn and many Iowa farmers with natural-air dryers harvest corn near 20%.
- Initial temperature: It was assumed that grain temperature would equal outdoor air temperature at harvest. On October 15 in central Iowa, this value averages about 50 F (10 C) (ASAE, 1983).
- Model years: Des Moines, Iowa weather from a recent 20-year period, fall, 1963 through spring, 1983, was used for the simulations.

Results and Discussion

As shown in Appendix B, NADWIS output includes date drying is complete, fan energy, final average moisture content, and maximum dry matter loss. In a number of trial runs using 1963-83 Des Moines weather data, airflow was varied in 0.1 cfm/bu increments until 90% drying success was achieved. Drying success is defined as completion of drying by May 20 with ≤ 0.5% dry matter loss in the layer with highest dry matter loss. Thompson was the first to propose 0.5% dry matter loss (Thompson, 1972) and 90% probability (Pierce and Thompson, 1978a) as criteria for drying success in simulation studies. These criteria have been generally accepted and were used to develop the airflow recommendations in MWPS-22 (MWPS, 1980).

Tables 6 and 7 summarize simulation results for drying 20 and 24% MCWB corn, respectively, harvested mid-October in central Iowa. Airflow is minimum required to achieve successful drying at least 18 years out of 20.

20% MCWB corn

Table 6 shows that stirring reduces initial airflow requirement for 90% successful drying of 20% MCWB corn from 16.7 to 11.1 L/s•t. (MWPS recommendation for unstirred 20% MCWB corn is a little less than 18 L/s•t (MWPS, 1980).) The reduced airflow requirement reduces fan input power from 3.0 kW to 0.4 kW (for 7-ring, 5.5-m diameter bins). Because stirring cuts both fan power requirement and drying time, mean energy use decreases 83%--from 57.53 to 9.72 kWh/t. Energy use figures from computer simulation are much lower than actual energy use in the field test with 20% MCWB corn. This is attributable largely to the high fan power and airflow used in the field test.

Stirring also reduced overdrying from 2.06 percentage points to 0.085 points. You might expect that years with low energy use (favorable drying weather) would have greater overdrying. Table 6 indicates little correlation between overdrying and energy use. So high energy costs are not necessarily offset by low overdrying costs, and sometimes (1972 for example), both costs are unusually high the same year.

<u>24% MCWB corn</u>

Table 7 shows that stirring cut initial airflow requirement for 90% successful drying of 24% MCWB corn almost in half--from 50.2 to 27.9 L/s•t. (MWPS recommends about 50 L/s•t for unstirred 24% MCWB corn (MWPS, 1980).) Average energy use in the stirred bin is less than half the unstirred value--62.44 vs. 128.68 kWh/t. Note the wide range of energy use between years in the unstirred bin--in 1972, the fan used 1.8 times the average value.

TABLE 6. Computer simulation results for 20% MCWB corn

October 15 harvest, Des Moines, Iowa
Maximum dry matter loss ≤ 0.5% at least 18 out of 20 years

Year	Fan energy (kWh/t)		Overdrying[a] (points w.b.)		Maximum dry matter loss (%)		Fall finish?	
	NS[b]	S[c]	NS	S	NS	S	NS	S
1963	55.3	11.5	1.5	0.1	0.45	0.47		
1964	65.0	10.2	2.4	0.1	0.45	0.41		
1965	56.8	10.6	1.2	0.0	0.32	0.31		
1966	52.3	9.8	1.3	0.1	0.25	0.22		
1967	56.0	9.7	2.0	0.1	0.17	0.16		
1968	59.8	10.0	1.9	0.1	0.28	0.25		
1969	54.5	8.9	2.3	0.1	0.18	0.15		
1970	55.3	8.7	3.1	0.1	0.28	0.24		
1971	71.0	12.7	1.2	0.1	0.53	0.55		
1972	74.7	11.5	3.1	0.0	0.45	0.37		
1973	54.5	8.9	1.8	0.1	0.28	0.22		
1974	58.3	10.0	1.5	0.0	0.32	0.29		
1975	54.5	9.3	1.9	0.0	0.32	0.30		
1976	50.1	7.4	3.4	0.1	0.17	0.12		
1977	56.8	9.5	1.9	0.2	0.38	0.30		
1978	56.8	10.2	1.4	0.0	0.30	0.28		
1979	53.8	8.2	3.0	0.2	0.37	0.29		
1980	46.3	7.3	2.5	0.1	0.20	0.16		
1981	55.3	9.8	1.6	0.1	0.26	0.19		
1982	63.5	10.2	2.2	0.1	0.26	0.22		
	-----	----	----	-----	-----	----	----	----
mean	57.53	9.72	2.06	0.085	19/20[d]	19/20	0/20[e]	0/20
standard deviation	6.66	1.32	0.68	0.059				

[a]Overdrying = 15.5 - (final average moisture) = percentage points, wet basis.

[b]NS: no stirring, 5.5-m dia. x 5.7-m high bin; 96.4 t corn; 3.0 kW input to fan motor; 16.7 L/s•t initial airflow.

[c]S: stirred twice (at beginning and end of drying); 5.5-m dia. x 5.7-m high bin; 82.9 t corn; 0.4 kW input to fan motor; 11.1 L/s•t initial airflow.

[d]Number of years with dry matter loss ≤ 0.5%.

[e]Number of years with drying complete before winter.

TABLE 7. Computer simulation results for 24% MCWB corn

October 15 harvest, Des Moines, Iowa
Maximum dry matter loss ≤ 0.5% at least 18 out of 20 years

Year	Fan energy (kWh/t)		Overdrying[a] (points w.b.)		Maximum dry matter loss (%)		Fall finish?	
	NS[b]	S[c]	NS	S	NS	S	NS	S
1963	118.1	56.9	2.3	0.1	0.77	0.71	x	x
1964	133.6	77.5	1.1	0.0	0.36	0.47	x	
1965	118.1	65.1	2.4	0.1	0.41	0.45	x	
1966	107.9	58.9	3.2	0.0	0.15	0.19	x	
1967	118.1	67.2	2.1	0.2	0.16	0.17	x	
1968	123.3	68.2	2.0	0.3	0.27	0.29	x	
1969	133.6	50.6	1.9	0.0	0.18	0.17	x	x
1970	133.6	55.8	1.7	0.1	0.36	0.36	x	
1971	143.8	74.4	2.0	0.0	0.75	0.81	x	
1972	236.3	78.6	1.1	0.1	0.34	0.43		
1973	113.0	61.0	2.4	0.1	0.32	0.32	x	
1974	107.9	62.0	1.6	0.1	0.39	0.36	x	
1975	102.7	64.1	1.9	0.0	0.28	0.34	x	
1976	133.6	46.5	3.0	0.0	0.12	0.10	x	x
1977	143.8	61.0	1.6	0.1	0.50	0.50	x	
1978	113.0	67.2	2.9	0.1	0.29	0.29	x	
1979	123.3	58.9	2.2	0.0	0.45	0.47	x	
1980	123.3	42.4	3.4	0.1	0.20	0.17	x	x
1981	123.3	56.9	3.0	0.1	0.29	0.26	x	x
1982	123.3	75.5	2.3	0.0	0.26	0.28	x	
mean	128.68	62.44	2.21	0.075	18/20[d]	18/20	19/20[e]	5/20
stardard deviation	27.76	9.79	0.65	0.079				

[a]Overdrying = 15.5 - (final average moisture) = percentage points, wet basis.

[b]NS: No stirring; 5.5-m dia. x 4.1-m high bin; 61.7 t corn; 13.2 kW input to fan motor; 50.2 L/s•t initial airflow.

[c]S: Stirred 3 times (at beginning and end of drying, and 20% avg. moisture); 5.5-m dia. x 5.7-m high bin; 74.3 t corn; 3.2 kW input to fan motor; 27.9 L/s•t initial airflow.

[d]Number of years with dry matter loss ≤ 0.5%.

[e]Number of years with drying complete before winter.

As expected, the unstirred field test bin used slightly less energy than the average simulation value because airflow was less. Although drying was successful in the unstirred bin in 1982-83, the fan is too small (or depth too great) to ensure success 18 years out of 20. The stirred test bins had higher airflow than necessary for 90% drying success and consequently used more energy than the simulated stirred bin.

Again, stirring reduced overdrying with no apparent correlation between overdrying and energy use. Because 24% MCWB corn requires greater airflow than 20% corn to prevent spoilage, drying is faster and more fall finishes can be expected. Stirring reduces the number of fall finishes for 24% corn.

Constant vs. increasing airflow

Tables 8 and 9 show the difference in results obtained when constant airflow is used instead of increasing airflow in simulation of unstirred drying. For 20% MCWB corn (Table 8), the difference is negligible--results are almost identical whether airflow is constant throughout drying or is increased each day using the equation from Figure 6. For 24% MCWB corn (Table 9), simulation results are slightly worse for constant airflow--mean energy use is about 4% greater, about 3% more overdrying occurs, and dry matter loss is a bit higher. The effect is not large, but using field test data to modify airflow in computer simulation does improve results for wet, unstirred corn.

Summary

A version of Thompson's storage model was modified to allow reasonably accurate simulation of stirred and unstirred natural-air drying. Data from field tests were used to calibrate and provide inputs to the model. A number of simulations for 20 and 24% MCWB corn were run to find minimum airflow required for drying with dry matter loss less than or equal to 0.5% in the worst layer at least 18 years out of 20. Computer simulation results indicate that stirring greatly reduces fan power requirements, energy use, and overdrying. Inserting an equation into the computer model to increase airflow as unstirred corn dries has no effect for 20% MCWB corn, but does improve drying results for 24% MCWB corn.

TABLE 8. Simulation results with constant and increasing airflow, unstirred 20% MCWB corn

October 15 harvest, Des Moines, Iowa, 96.4 t
3.0 kW fan motor input, 16.7 L/s•t initial airflow

Year	Fan energy (kWh/t) IA[b]	CA[c]	Overdrying[a] (points w.b.) IA	CA	Maximum dry matter loss (%) IA	CA	Fall finish? IA	CA
1963	55.3	55.3	1.5	1.5	0.45	0.45		
1964	65.0	65.0	2.4	2.4	0.45	0.45		
1965	56.8	56.8	1.2	1.2	0.32	0.32		
1966	52.3	52.3	1.3	1.3	0.25	0.24		
1967	56.0	56.0	2.0	2.0	0.17	0.17		
1968	59.8	59.8	1.9	1.9	0.28	0.28		
1969	54.5	54.5	2.3	2.3	0.18	0.18		
1970	55.3	56.0	3.1	3.1	0.28	0.28		
1971	71.0	71.0	1.2	1.2	0.53	0.54		
1972	74.7	74.7[d]	3.1	3.1	0.45	0.45		
1973	54.5	54.5	1.8	1.8	0.28	0.28		
1974	58.3	58.3	1.5	1.5	0.32	0.32		
1975	54.5	54.5	1.9	1.9	0.32	0.32		
1976	50.1	50.1	3.4	3.3	0.17	0.17		
1977	56.8	57.5	1.9	2.0	0.38	0.38		
1978	56.8	56.8	1.4	1.4	0.30	0.30		
1979	53.8	53.8	3.0	2.9	0.37	0.37		
1980	46.3	47.1	2.5	2.8	0.20	0.21		
1971	55.3	55.3	1.6	1.6	0.26	0.25		
1982	63.5	63.5	2.2	2.2	0.26	0.26		
mean	57.53	57.64	2.06	2.07	19/20[e]	19/20	0/20[f]	0/20
standard deviation	6.66	6.58	0.68	0.67				

[a]Overdrying = 15.5 - (final average moisture) = percentage points, wet basis.

[b]IA: airflow increases as corn dries.

[c]CA: constant airflow throughout drying.

[d]Drying not complete by May 20.

[e]Number of years with dry matter loss ≤ 0.5%.

[f]Number of years with drying complete before winter.

TABLE 9. Simulation results with constant and increasing airflow, unstirred 24% MCWB corn

October 15 harvest, Des Moines, Iowa, 61.7 t
13.2 kW fan motor input, 50.2 L/s•t initial airflow

	Fan energy (kWh/t)		Overdrying[a] (points w.b.)		Maximum dry matter loss (%)		Fall finish?	
Year	IA[b]	CA[c]	IA	CA	IA	CA	IA	CA
1963	118.1	128.4	2.3	2.3	0.77	0.80	x	x
1964	133.6	138.7	1.1	1.3	0.36	0.38	x	x
1965	118.1	123.3	2.4	2.5	0.41	0.42	x	x
1966	107.9	113.0	3.2	2.8	0.15	0.15	x	x
1967	118.1	123.3	2.1	2.3	0.16	0.16	x	x
1968	122.3	128.4	2.0	2.2	0.27	0.27	x	x
1969	133.6	138.7	1.9	2.0	0.18	0.19	x	x
1970	133.6	138.7	1.7	1.9	0.36	0.37	x	x
1971	143.8	149.0	2.0	2.0	0.75	0.76	x	x
1972	236.3	241.4	1.1	1.3	0.34	0.34		
1973	113.0	118.1	2.4	2.3	0.32	0.33	x	x
1974	107.9	113.0	1.6	1.7	0.39	0.40	x	x
1975	102.7	107.9	1.9	1.9	0.28	0.31	x	x
1976	133.6	138.7	3.0	3.1	0.12	0.12	x	x
1977	143.8	143.8	1.6	1.6	0.50	0.51	x	x
1978	113.0	118.1	2.9	3.1	0.29	0.30	x	x
1979	123.3	128.4	2.2	2.3	0.45	0.46	x	x
1980	123.3	128.4	3.4	3.7	0.20	0.21	x	x
1981	123.3	123.3	3.0	2.9	0.29	0.30	x	x
1982	123.3	128.4	2.3	2.2	0.26	0.27	x	x
	------	------	----	----	-----	-----	-----	-----
mean	128.68	133.55	2.21	2.27	18/20[d]	17/20	19/20[e]	19/20
standard deviation	27.76	27.63	0.65	0.62				

[a]Overdrying = 15.5 - (final average moisture) = percentage points, wet basis.

[b]IA: airflow increases as corn dries.

[c]CA: constant airflow throughout drying.

[d]Number of years with dry matter loss ≤ 0.5%.

[e]Number of years with drying complete before winter.

ECONOMIC ANALYSIS

Both the field tests and computer simulations have shown that stirring reduces overdrying, required fan size, and energy purchases for natural-air drying. But are these cost savings large enough to offset the cost of owning and operating stirring equipment? To help answer this question, equipment costs from a local dealer and energy consumption and overdrying figures from the computer simulations were used in an economic analysis.

Bin capacities were calculated using bulk density values from the field tests. Because 5.5-m diameter bins were used in the field tests and it was believed that initial bulk density might be a function of bin diameter, 5.5-m diameter bins were also used in the economic analysis. First cost of stirring equipment per unit of bin capacity tends to decrease as bin diameter increases. So if stirring is economically feasible in 5.5-m bins, we can be reasonably confident that it will be in large diameter bins as well.

A net-revenue method suggested by Smith (1973) was used to analyze the economic feasibility of natural-air stir drying. The economic model is described below.

$$AEX = \frac{(AER-AEM)(1-\tau) - B\ (a/p) + S\ (a/f) + \tau\ (AED)}{CAP}$$

where AEX = net, annual, after-tax revenue (\$/t)

= value of dried corn - drying cost

AER = total value of corn ($)

= (weight marketed)(price of corn)

Weight is reduced when corn is overdried.

AEM = energy, repair and maintenance, and insurance costs ($)

= (fan + stirrer energy)(price of electricity) + (insurance rate)(first cost) + (stirrer repairs and maintenance)

τ = producer's income tax bracket

B = actual first cost of equipment - tax credits

(a/p) = factor which converts first cost to annual equivalent using interest rate i and life n

$$= \frac{i\,(1 + i)^n}{(1 + i)^n - 1}$$

S = salvage value at end of analysis period ($)

(a/f) = factor which converts a future sum to an annual equivalent using interest rate i and life n

$$= \frac{i}{(1 + i)^n - 1}$$

AED = annual equivalent value of depreciation ($)

CAP = bin capacity (t)

Inputs to the economic model were selected based on conditions in 1985 in central Iowa.

- Price of corn: $100/t ($2.54/bu) and $120/t ($3.05/bu), where 1 t = 1000 kg at 15.5% MCWB, but less than 1000 kg at less than 15.5%.

- Price of electricity: \$.05/kWh and \$.10/kWh.
- Fan energy: used mean values from Tables 6 and 7.
- Stirrer energy: used 96 kWh for stirring twice (2)(48 h)(1 kW) and 144 kWh for stirring three times (3)(48 h)(1 kW).
- Insurance rate: assumed to be 0.5% stirrer first cost per year.
- Bin repairs and maintenance: 2% fan and bin first cost per year.
- Income tax bracket: used 30%.
- First cost: received prices from Stockdales, Iowa Falls, Iowa, (February, 1985) for installed costs of stirrers and fully equipped bins (fans, spreaders, ladders, vents, unload augers, full perforated floors); subtracted 10% for investment credit.
- Interest rate: assumed producer would borrow money at 15% interest.
- Life: used 20 years in the analysis.
- Depreciation: used the annual equivalent of a five year write-off;

  $$AED = \frac{(\text{actual first cost} - S)}{5}\,(p/a)\,(a/p)$$

  where (p/a) converts five years depreciation to a present equivalent basis which is then converted to an annual equivalent over 20 years.

- Salvage value: assumed to be 0 for both bin and stirrer.

First costs from Stockdales and bin capacities are listed in Table 10. Revenue equations and results of the analyses are presented in Tables 11 and 12.

For 20% MCWB corn (Table 11), stirring results in lower net revenues when electricity costs \$.05/kWh, but greater net revenues at \$.10/kWh. Setting AEX equations for the two drying systems equal to one another gives equivalent net revenues when corn brings \$100/t and electricity costs \$0.084/kWh or when corn is \$120/t and electricity costs \$0.074/kWh. In other words, stirring brings greater net revenues when corn is \$100/t and electricity costs more than \$0.084/kWh, or when corn brings \$120/t and electricity costs more than \$0.074/kWh. For 24% MCWB corn (Table 12), stirring results in greater new revenues for all electricity prices between \$0.05 and \$0.10/kWh.

Based on the results of this study, it seems that corn producers using natural-air to dry 24% MCWB corn in Iowa in mid-October can justify installation of stirring equipment. For producers drying 20% MWCB corn, stirring equipment may not be economically feasible unless electricity prices are high.

TABLE 10. Dryer costs and capacities

	S[a]	NS[b]	S	NS
Corn moisture, % wb	24	24	20	20
Bin diameter, ft	18	18	18	18
m	5.5	5.5	5.5	5.5
Bin sidewall height,				
rings	7	5	7	7
m	5.7	4.1	5.7	5.7
Bin capacity, bu	2925	2428	3265	3794
t	74.3	61.7	82.9	96.4
Nominal fan output,				
hp	3	13	0.5	3.0
kW	2.2	9.7	0.4	2.2
Cost, $[c]				
Bin	6801	6050	6550	6801
Stirrer	1791	--	1791	--
Total	8592	6050	8341	6801

[a]Equipped with stirrer.

[b]Not equipped with stirrer.

[c]Values are from Stockdales, Iowa Falls, Iowa, February, 1985.

TABLE 11. Net revenue comparisons, 20% MCWB corn

Price of corn, P_{corn} ($/t)	Price of electricity, P_{elec} ($/kWh) 0.05 NS[a]	0.05 S[b]	0.10 NS	0.10 S
	Net revenue, AEX ($/t)			
100	57.21	56.10	55.20	55.72
120	70.88	70.09	68.86	69.71

[a]NS: no stirring; 96.4 t corn
$AEX = 0.6834\ P_{corn} - 40.27\ P_{elec} - 9.112$

[b]S: stirred twice (at beginning and end of drying); 82.9 t corn
$AEX = 0.6993\ P_{corn} - 7.615\ P_{elec} - 13.44$

TABLE 12. Net revenue comparisons, 24% MCWB corn

Price of corn, P_{corn} ($/t)	Price of electricity, P_{elec} ($/kWh) 0.05 NS[a]	0.05 S[b]	0.10 NS	0.10 S
	Net revenue, AEX ($/t)			
100	51.05	52.24	46.55	49.99
120	64.69	66.23	60.18	63.98

[a]NS: no stirring; 61.7 corn
$AEX = 0.6822\ P_{corn} - 90.08\ P_{elec} - 12.67$

[b]S: stirred three times (at beginning and end of drying, and at 20% avg. moisture); 74.3 t corn
$AEX = 0.6993\ P_{corn} - 45.06\ P_{elec} - 15.44$

SUMMARY AND CONCLUSIONS

Field studies and computer simulations were used to develop and test management recommendations for natural-air stir dryers and to evaluate the economic feasibility of adding grain stirrers to natural-air dryers. Some observations and conclusions are:

- During natural-air drying of unstirred corn, airflow resistance decreased and airflow increased. When increasing airflow was simulated, drying performance improved slightly for 24% MCWB, but showed no change for 20% MCWB compared to simulation with constant airflow.
- Initial stirring of wet, spreader-placed corn greatly reduced airflow resistance and increased airflow. Stirring 25% MCWB corn cut airflow resistance 50% and increased airflow 41%. Stirring 20% MCWB corn cut airflow resistance 33% and increased airflow 28%.
- Repeated stirring increased airflow resistance and decreased airflow from values measured after the first stirring.
- After the first stirring, bulk density changes did not fully explain airflow resistance changes in stirred corn.

- Effect of stirring on airflow and airflow resistance was the same whether corn was stirred during bin filling or after the bin was full. Thus, corn producers should stir corn during bin filling to avoid the difficulty and potential equipment damage and danger from starting stirrers in full bins.
- Initial moisture content did not affect initial bulk density of spreader-placed corn, but greatly affected initial airflow resistance. Initial bulk density was nearly the same for 20% and 25% MCWB corn, but Shedd's curve multiplier was 1.3 times greater for the wetter corn.
- Stirring moved fines toward the drying floor. Fines on the floor formed a crust that might have increased airflow resistance.
- Single stirring augers produced an average of about 1.7 kg dry matter BCFM per hour of stirring. If BCFM content of all loads is averaged at time of sale, stirring should not increase BCFM content enough to cause market discounts.
- For natural-air drying bins equipped with the same size fan, stirring reduced drying time, energy use, and overdrying.

- Airflow inputs to the computer simulation model had to be reduced to 74% of values from fan performance curves to avoid overprediction of drying. Use of more than 57.5% of electric power input to the fan to calculate temperature rise also resulted in overprediction of drying.
- When natural-air drying systems were compared on the basis of equal probability of drying success, stirring allowed use of smaller fans and reduced energy consumption and overdrying.
- An economic analysis indicated that installing stirrers in natural-air corn dryers increased net revenues for 24% MCWB corn and increased net revenues for 20% MCWB corn when electricity prices were high.

SUGGESTIONS FOR FUTURE STUDY

Here are some questions that were not answered by this study, but are worth future investigation:

- The effect of drying corn to final moistures other than 15.5% (14% and 17%, for example) on net revenues from stir drying.
- Economic feasibility of using supplemental heat to speed stir drying.
- Effect of variables like tax bracket, interest rate, and investment credit on net revenue. Economic analyses should be redone if proposed changes to tax law are passed.
- Effect of reducing probability of drying success to 85% or even 75%.
- Effect of stirring on kernel orientation, and kernel orientation on airflow resistance.
- Airflow resistance of layers of loose and crusted fines on perforated floors.

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PROBABLE LIFE 15 SALVAGE RATIO .1

K VALUES ARE	.2	.3	.4	.5	.6
DELTA % AT AGE 1	0	0	0	0	0
DELTA % AT AGE 2	17.80645	10.40439	6.522973	4.264303	2.864936
DELTA % AT AGE 3	20.45424	12.80931	8.607114	6.030635	4.342431
DELTA % AT AGE 4	22.18205	14.46615	10.12265	7.38599	5.538443
DELTA % AT AGE 5	23.49576	15.77011	11.35716	8.528606	6.581894
DELTA % AT AGE 6	24.56809	16.86194	12.41749	9.535271	7.524835
DELTA % AT AGE 7	25.48048	17.80992	13.35692	10.44537	8.394711
DELTA % AT AGE 8	26.27829	18.65289	14.20643	11.28229	9.208179
DELTA % AT AGE 9	26.98953	19.41528	14.98586	12.06127	9.976286
DELTA % AT AGE 10	27.63287	20.11358	15.70879	12.79291	10.70682
DELTA % AT AGE 11	28.22132	20.75949	16.38497	13.48491	11.40552
DELTA % AT AGE 12	28.76444	21.36163	17.02169	14.14309	12.07676
DELTA % AT AGE 13	29.26939	21.92659	17.62455	14.77198	12.724
DELTA % AT AGE 14	29.74172	22.45948	18.19797	15.37516	13.34999
DELTA % AT AGE 15	30.18592	22.9644	18.74549	15.95556	13.95699

.7	.8	.9	1	1.1	1.2
0	0	0	0	0	0
1.961644	1.361764	.9551328	.6752601	.480379	.3434458
3.1867	2.37097	1.782341	1.350521	1.029715	.7890312
4.232579	3.279436	2.567279	2.025781	1.608487	1.283524
5.176811	4.128099	3.325966	2.701042	2.207243	1.812719
6.052006	4.934898	4.065714	3.376303	2.821313	2.369313
6.875847	5.70983	4.790712	4.051563	3.447368	2.948763
7.659298	6.459227	5.503667	4.726825	4.085	3.547939
8.409753	7.187438	6.206473	5.402084	4.731329	4.164534
9.132509	7.897619	6.900525	6.077345	5.385811	4.796777
9.831511	8.592156	7.586892	6.752606	6.047617	5.443253
10.50982	9.272914	8.266416	7.427865	6.716085	6.102807
11.16985	9.94139	8.939784	8.103126	7.390666	6.77448
11.81356	10.5988	9.607556	8.778386	8.0709	7.457453
12.44257	11.24617	10.27021	9.453649	8.756391	8.151024

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APPENDIX A: RAW FIELD-TEST DATA

TABLE A1. East bin data, 1982-83

2910 bu shelled corn, 18-ft dia. bin, 5- to 7-hp fan (Figure 5a)

Date	Drying time (h)	Avg. MC (% wb)	Corn depth (ft)	Corrected SP (in. H2O)	Airflow (cfm/bu)	SCM	Comments
10-21	18	24.73	14.93	4.13	2.02	1.20	Stirrer running
	21			4.20	1.95		
	26			4.09	2.06		
	40			4.08	2.07		
	48		15.09	4.10	2.05	1.18	Stopped stirrer
	69			4.12	2.03		
	74			4.12	2.03		
	96			4.17	1.98		
	119			4.18	1.97		
	136			4.12	2.03		
10-27	144	24.9	14.76	4.09	2.06	1.20	
	168			4.23	1.92		Started stirrer
	194			4.29	1.86		
	217		14.44	4.27	1.88	1.48	Stopped stirrer
	240			4.37	1.79		
	245			4.43	1.73		
	269			4.38	1.78		
11-3	300	20.7		4.22	1.93		
	324		14.08	4.17	1.98	1.35	Started stirrer
	372		14.08	4.40	1.76	1.74	Stopped stirrer
	398			4.55	1.62		
	415			4.38	1.78		
	439			4.42	1.74		
11-10	470	19.9		4.49	1.68		
	493		13.81	4.50	1.67	1.92	Started stirrer
	541		13.75	4.29	1.86	1.56	Stopped stirrer
	563			4.29	1.86		
	589			4.48	1.68		
11-16	614			4.40	1.76		
	637	18.6		4.52	1.65		
	661		13.62	4.41	1.75	1.80	Started stirrer
	687			4.38	1.78		
	710		13.71	4.39	1.77	1.69	Stopped stirrer
	732			4.32	1.84		
11-22	751			4.38	1.78		
	794	17.7		--	--		
	819		13.58	4.30	1.85	1.58	Started stirrer
	848			4.33	1.83		
11-27	871		13.48	4.25	1.90	1.50	Stopped stirrer
	895			4.34	1.82		
	920			4.41	1.75		
	944			4.44	1.72		
12-1	965	17.3		4.57	1.61		
	990		13.45	4.55	1.62	1.99	Started stirrer
12-3	1012	17.0		4.22	1.93		Winter shutdown
12-4	1012		13.71	--	--		Stopped stirrer
4-16	1012	17.2	13.65	4.34	1.82	1.67	Spring startup
4-17	1035			4.21	1.94		Fan off 2 days
4-19	1035			4.40	1.76		
	1064			4.32	1.84		
	1088		13.58	4.35	1.81	1.69	Started stirrer
	1112			4.23	1.92		
4-23	1136		13.35	4.16	1.99	1.42	Stopped stirrer
	1160			4.24	1.91		
	1182			4.41	1.75		
	1206			4.27	1.88		
	1234	14.9		4.20	1.95		
4-28	1254	14.10	12.93	4.29	1.86	1.67	Drying complete; started stirrer
4-30			12.93				

TABLE A2. Center bin data, 1982-83

2898 bu shelled corn, 18-ft dia. bin, 5- to 7-hp fan (Figure 5a)

Date	Drying time (h)	Avg. MC (% wb)	Corn depth (ft)	Corrected SP (in. H2O)	Airflow (cfm/bu)	SCM	Comments
10-21	18	24.61	14.01	4.77	1.46	2.43	Started stirrer
	21			4.45	1.72		
	26			4.29	1.87		
	40			4.08	2.08		
	48			4.05	2.11		
10-24	69		14.70	4.12	2.04	1.22	Stopped stirrer
	74			4.12	2.04		
	96			4.17	1.99		
	119			4.18	1.98		
	136			4.12	2.04		
10-27	144	24.2	14.44	4.09	2.07	1.23	
	168			4.23	1.93		
	194			4.29	1.87		
10-30	217		14.17	4.27	1.89	1.51	
	240			4.26	1.90		
	245			4.43	1.74		
	269			4.33	1.83		
11-3	300	21.3		4.22	1.94		
	324		13.94	4.12	2.04	1.27	
	372		13.91	4.30	1.86	1.55	
	398			4.39	1.78		
	415			4.24	1.92		
	439			4.17	1.99		
11-10	470	19.3		4.29	1.87		
	493		13.78	4.20	1.96	1.39	Started stirrer
	541		13.62	4.10	2.06	1.31	Stopped stirrer
	563			4.20	1.96		
	589			4.29	1.87		
	614			4.20	1.96		
11-17	637	17.6		4.22	1.94		
	661		13.45	4.21	1.95	1.49	
	687			4.38	1.78		
	710		13.39	4.39	1.78	1.73	
	732			4.37	1.79		
	751			4.33	1.83		
11-24	794	17.7		--	--		
	819		13.29	4.35	1.81	1.72	
	848			4.33	1.83		
11-27	871		13.22	4.20	1.96	1.44	
	895			4.34	1.82		
	920			4.41	1.76		
	944			4.44	1.73		
12-1	965	16.7		4.51	1.66		
	990		13.19	4.55	1.63	2.03	
12-3	1012	16.3	13.12	4.32	1.84		Winter shutdown
4-16	1012	16.5	13.06	4.34	1.82	1.75	Spring startup
4-17	1035			4.21	1.95		Fan off 2 days
4-19	1035			4.40	1.77		
	1064			4.32	1.84		
	1088		12.99	4.35	1.81	1.76	
	1112			4.33	1.83		
4-23	1136		12.93	4.36	1.80	1.77	
	1160			4.24	1.92		
	1182			4.41	1.76		
	1206			4.27	1.89		
	1234	13.9		4.20	1.96		
4-28	1254	13.65	12.60	4.29	1.87	1.70	Drying complete; started stirrer
4-30			12.76				

TABLE A3. West bin data, 1982-83

2880 bu shelled corn, 18-ft dia. bin, 5- to 7-hp fan (Figure 5a)

Date	Drying time (h)	Avg. MC (% wb)	Corn depth (ft)	Corrected SP (in. H20)	Airflow (cfm/bu)	SCM	Comments
10-21	18	24.66	13.98	4.72	1.50	2.25	
	21			4.79	1.45		
	26			4.78	1.46		
	40			4.75	1.48		
	48			4.85	1.42		
10-24	69			4.87	1.41		
	74			4.81	1.44		
	96			4.83	1.43		
	119			4.84	1.42		
	136			4.73	1.50		
10-27	144	25.0	13.85	4.75	1.48	2.45	
	168			4.89	1.39		
	194			4.90	1.39		
10-30	217		13.68	4.78	1.46	2.50	
	240			4.83	1.43		
	245			4.94	1.37		
	269			4.82	1.43		
11-3	300	22.1		4.80	1.45		
	324		13.52	4.69	1.53	2.31	
	372		13.52	4.85	1.42	2.76	
	398			4.96	1.36		
	415			4.82	1.43		
	439			4.71	1.51		
11-10	470	20.0		4.89	1.39		
	493		13.39	4.71	1.51	2.35	
11-13	541		13.32	4.63	1.57	2.32	
	563			4.72	1.50		
	589			4.77	1.47		
	614			4.64	1.56		
11-17	637	19.4		4.72	1.50		
	661		13.22	4.66	1.55	2.35	
	687			4.79	1.45		
11-20	710		13.19	4.79	1.45	2.59	
	732			4.72	1.50		
	751			4.72	1.50		
11-24	794	17.5		--	--		
	819		13.09	4.64	1.56	2.36	
	848			4.71	1.51		
11-27	871		13.03	4.49	1.69	2.03	
	895			4.63	1.57		
	920			4.61	1.59		
	944			4.64	1.56		
12-1	965	17.3		4.72	1.50		
	990		12.99	4.75	1.48	2.61	
	1012			4.61	1.59		
12-4	1038		12.93	4.56	1.63	2.20	
	1086			4.66	1.55		
12-7	1102	16.0	12.93	--	--		Winter shutdown
4-16	1102	16.3	12.93	4.63	1.57	2.39	Spring startup
4-17	1125			4.50	1.68		Fan off 2 days
4-19	1125			4.64	1.56		
	1154			4.57	1.62		
	1178		12.93	4.61	1.59	2.23	
	1202			4.59	1.61		
4-23	1226		12.86	4.57	1.62	2.22	
	1249			4.50	1.68		
	1271			4.62	1.58		
	1295			4.69	1.53		
	1323	13.9		4.50	1.68		
4-28	1344		12.60	4.50	1.68	2.10	
	1371			4.40	1.78		
	1390			4.47	1.71		
5-1	1416	13.02	12.37	4.24	1.93	1.63	Drying complete

TABLE A4. East bin data, 1983-84

3093 bu shelled corn, 18-ft dia. bin, 3-hp fan (Figure 5b)

Date	Drying time (h)	Avg. MC (% wb)	Corn depth (ft)	Corrected SP (in. H20)	Airflow (cfm/bu)	SCM	Comments
10-14	29	19.54		2.51	1.37		Stirrer running
	48			2.65	1.27		
	65		14.57	2.56	1.33	1.26	Stopped stirrer
	86			2.55	1.34		
	115			2.50	1.37		
	134			2.38	1.45		
	164			2.38	1.45		
10-21	182	19.4	14.37	2.41	1.43	1.12	
	215			2.56	1.33		
	235			2.69	1.24		
	254			2.61	1.30		
	285			2.62	1.29		
	311			2.65	1.27		
	332			2.81	1.16		
10-28	361	18.5		2.66	1.26		
	380		14.14	2.55	1.34	1.29	
	384			2.49	1.38		
	405			2.44	1.41		
	423			2.56	1.33		
	454			2.80	1.16		
	478			2.77	1.18		
	493			2.54	1.34		
11-7	519	17.0	13.85	2.45	1.41	1.18	
	547			2.54	1.34		
	574			2.71	1.23		
	598			2.78	1.18		
	614			2.73	1.21		
	638			2.75	1.20		
	662			2.66	1.26		
	687	16.5	13.91	2.58	1.32	1.42	
11-12	712	16.5	13.91	2.51	1.37	1.29	Winter shutdown
4-15	712	16.6	13.91	2.75	1.20	1.65	Spring startup
	730			2.71	1.23		
	754			2.63	1.28		
4-17	763			2.64	1.28		
	778			2.60	1.30		
	802			2.54	1.34		
	826			2.40	1.44		
4-21	859			2.19	1.57		
	900			2.66	1.26		
	922		13.78	2.66	1.26	1.61	Started stirrer
	946			2.45	1.41		
4-26	970	15.37	13.81	2.72	1.22	1.64	Drying complete;
5-3				2.59	1.31	1.44	stopped stirrer

TABLE A5. Center bin data, 1983-84

3063 bu shelled corn, 18-ft dia. bin, 5- to 7-hp fan (Figure 5a)

Date	Drying time (h)	Avg. MC (% wb)	Corn depth (ft)	Corrected SP (in. H20)	Airflow (cfm/bu)	SCM	Comments
10-14	28	19.60		4.02	2.03		Stirrer running
	33			4.08	1.97		
	50		14.37	4.02	2.03	1.12	Stopped stirrer
	71			3.95	2.09		
	100			3.90	2.14		
	119			3.87	2.17		
	149			4.06	1.99		
10-21	167	18.7	14.21	3.99	2.05	1.12	
	200			4.06	1.99		
	220			4.07	1.98		
	238			4.02	2.03		
	269			4.06	1.99		
	296			4.03	2.02		
	317			4.06	1.99		
10-28	346	17.2		4.11	1.94		
	365		13.94	3.97	2.07	1.10	
	369			3.96	2.08		
	390			3.91	2.13		
	406			4.03	2.02		
	419			4.27	1.79		
	443			4.16	1.89		
	458			4.11	1.94		
11-4	484	15.8	13.55	3.99	2.05	1.18	
	512		13.52	4.09	1.96	1.32	
	539			4.12	1.93		Started stirrer
	563			4.09	1.96		
11-8	578	15.8	13.68	4.09	1.96	1.30	Winter shutdown; stopped stirrer
4-15	578	15.6	13.58	4.07	1.98	1.25	Spring startup
	596			4.12	1.93		
	620		13.55	4.07	1.98	1.25	Started stirrer
	629			4.06	1.99		
	644			4.00	2.05		
4-19	668	15.18	13.65	3.94	2.10	1.11	Drying complete;
5-3				3.96	2.08	1.12	stopped stirrer

TABLE A6. West bin data, 1983-84

3118 bu shelled corn, 18-ft dia. bin, 5- to 7-hp fan (Figure 5a)

Date	Drying time (h)	Avg. MC (% wb)	Corn depth (ft)	Corrected SP (in. H2O)	Airflow (cfm/bu)	SCM	Comments
10-14	28	19.72	4.42	1.62			
	33			4.53	1.53		
	50		14.11	4.47	1.58	1.76	
	71			4.39	1.65		
	100			4.50	1.56		
	119			4.37	1.67		
	149			4.41	1.63		
10-21	167	19.0	14.01	4.48	1.57	1.88	
	200			4.56	1.51		
	220			4.47	1.58		
	238			4.40	1.64		
	269			4.45	1.60		
	296			4.48	1.57		
	317			4.58	1.49		
10-28	346	18.0		4.51	1.55		
	365		13.75	4.31	1.72	1.57	
	369			4.35	1.69		
	390			4.25	1.78		
	406			4.37	1.67		
	419			4.58	1.49		
	443			4.52	1.54		
	458			4.41	1.63		
11-4	484	16.1	13.71	4.28	1.75	1.56	
	512			4.39	1.65		
	539			4.42	1.62		
	563			4.55	1.51		
	578			4.50	1.56		
	602			4.49	1.56		
	626			4.45	1.60		
	651	15.5	13.52	4.30	1.73	1.59	
11-12	676	15.6	13.52	4.34	1.69	1.69	Winter shutdown
4-15	676	15.6	13.48	4.48	1.57	1.95	Spring startup
	694			4.52	1.54		
	718			4.37	1.67		
	727			4.47	1.58		
	742			4.40	1.64		
	766			4.34	1.69		
	790			4.25	1.78		
4-21	823			4.18	1.84		
	864			4.42	1.62		
	886			4.34	1.69		
	910			4.34	1.69		
4-26	934	14.32	13.39	4.58	1.49	2.14	Drying complete
5-3				4.52	1.54	1.99	

APPENDIX B: FORTRAN LISTING OF NADWIS

```
//NAOWIS        JOB
//STEP1  EXEC  FORTG,TIME.GO=(2,0)
//FORT.SYSIN  DD  $
      COMMON/GRNDRY/GRNHAR(6,100,3),FALWTH(150,3),STORGR(6,20,7),
     $IPRT,SUPHET(6,2),IDATE(150,3),IFINSH,FMTA,FMTM,GRNSTA,
     $BIN(6,4),HEAADD,CUMKWH,FANHRS,ICOUNT,ISTIR,CFMPB,
     $NB,NY,IDAY,ISDAY,IFANON,LAYER,MAXLAY,RH,LPRINT,PR
      WRITE(1,4001)
4001  FORMAT('1',30X,'SUMMARY OF SIMULATED DRYER RESULTS' /' ',
     $35X,'FALL SHUT DOWN CONDITIONS'//' ',
     $'            BIN  FAN       FAN     KWHS  GRAIN MOISTURE    ',
     $'DETERIORATION  GRAIN        TEMP BIN FAN    STIR  TIMES'/' ',
     $'YEAR BUSHELS NO.      OFF  HOURS     USED  AVG  MAX LAYER  ',
     $'AVG  MAX LAYER   TEMP CFM/BU RISE DIA  KW    OPT. STIRRED',
     $' MCI')
      WRITE(3,4003)
4003  FORMAT('1',30X,'SUMMARY OF SIMULATED DRYER RESULTS' /' ',
     $35X,'FINAL SHUT DOWN CONDITIONS'//' ',
     $'            BIN  FAN       FAN     KWHS  GRAIN MOISTURE    ',
     $'DETERIORATION  GRAIN        TEMP BIN FAN    STIR  TIMES'/' ',
     $'YEAR BUSHELS NO.      OFF  HOURS     USED  AVG  MAX LAYER  ',
     $'AVG  MAX LAYER   TEMP CFM/BU RISE DIA  KW    OPT. STIRRED',
     $' MCI')
C ENTER NUMBER OF BINS (1 TO 6)
      N=2
C
C ENTER BIN PARAMETERS
C   L=BIN NUMBER
C   K=1, BIN DIAMETER (FT)
C   K=2, FAN INPUT POWER (KW)
C   K=3, INITIAL AIRFLOW (CFM/BU)
C   K=4, STIRRING OPTION
C        -2.0:  NO STIRRING, CONSTANT AIRFLOW
C        -1.0:  STIRRED ONCE, CONSTANT AIRFLOW
C         0.0:  NO STIRRING, CHANGING AIRFLOW
C         1.0:  2 OR 3X STIRRING, CHANGING AIRFLOW
C         2.0:  WEEKLY STIRRING, CHANGING AIRFLOW
      DO 10 L=1,N
10    BIN(L,1)=18.0
      BIN(1,2)=15.0
      BIN(1,3)=2.8
      BIN(1,4)=0.0
      BIN(2,2)=3.6
      BIN(2,3)=1.6
      BIN(2,4)=1.0
C
C ENTER SUPPLEMENTAL HEAT
C   L=BIN NUMBER
C   K=1, ELECTRIC HEAT (BTU/MIN)
C   K=2, NON-ELECTRIC HEAT (F)
      DO 20 L=1,N
      SUPHET(L,1)=0.0
20    SUPHET(L,2)=0.0
C
C PROGRAM CALCULATES FAN HEAT EVEN IF SUPHET=0
C
C ENTER PRINT OPTION
C   LPRINT=-1, SUMMARY ONLY
C   LPRINT=0, SHUTDOWN VALUES
C   LPRINT=1, EVERY 2 WEEKS
```

```
C   LPRINT=2, EVERY WEEK
C   LPRINT=3, DAILY
       LPRINT=-1
C
C LPRINT OF 0 OR LESS RECOMMENDED TO AVOID MASSIVE PRINTOUTS
C
C ENTER DESIRED FINAL AVG MCWB
       FMTA=15.5
C ENTER DESIRED FINAL MAX MCWB
       FMTM=15.5
C ENTER NUMBER OF LAYERS TO BE MODELED (1 TO 20)
       MAXLAY=10
C
C MAXLAY=10 USUALLY GIVES SUFFICIENT ACCURACY
C
C      ZERO GRNHAR ARRAY
          DO 982 I4=1,N
          DO 982 J4=1,100
          DO 982 K4=1,3
982     GRNHAR(I4,J4,K4)=0.0
C
C ENTER HARVEST DATE (1 TO 100)
C   1=SEPT 7, 100=DEC 16
       ISDAY=38
       LISDAY=ISDAY+1
C ENTER CORN PARAMETERS
C   L=BIN NUMBER
C   K=1, BUSHELS IN BIN
C   K=2, INITIAL MOISTURE (%WB)
C   K=3, INITIAL TEMP (F)
C   BIN IS FULL WHEN GRNHAR(L,ISDAY,1)=-1.0
       DO 25 L=1,N
       GRNHAR(L,ISDAY,2)=24.0
       GRNHAR(L,ISDAY,3)=50.0
25     GRNHAR(L,LISDAY,1)=-1.0
       GRNHAR(1,ISDAY,1)=2428.
       GRNHAR(2,ISDAY,1)=2925.
C
C ENTER YEARS TO BE MODELED (63 TO 83)
       DO 30 IYRMOD=63,82
C
C      ZERO STORGR ARRAY
          DO 981 I3=1,N
          DO 981 J3=1,20
          DO 981 K3=1,7
981       STORGR(I3,J3,K3)=0.0
       NY=IYRMOD-50
       CALL WEATHR(IYRMOD)
       WRITE(1,4005)
       WRITE(3,4005)
4005   FORMAT(' ')
       DO 40 L=1,N
       NB=L
       CALL FALDRY
40     CONTINUE
30     CONTINUE
       STOP
       END
C
       SUBROUTINE WEATHR(IYRMOD)
```

```
      COMMON/GRNDRY/GRNHAR(6,100,3),FALWTH(150,3),STORGR(6,20,7),
     *IPRT,SUPHET(6,2),IDATE(150,3),IFINSH,FMTA,FMTM,GRMSTA,
     *BIN(6,4),HEAADD,CUMKWH,FANHRS,ICOUNT,ISTIR,CFMPB,
     *NB,NY,IDAY,ISDAY,IFANON,LAYER,MAXLAY,RH,LPRINT,PR
       NR=NY
       DO 984 I6=1,150
       J6=I6-50
       IF(J6.GT.0)GO TO 985
       READ(NR,304)
       GO TO 984
  985  READ(NR,304)(IDATE(J6,L6),L6=1,3),(FALWTH(J6,K6),K6=1,3)
  984  CONTINUE
  304  FORMAT(3A4,2F6.1,2X,F8.6)
       NR = NR + 1
       IF(NR.GT.33) RETURN
      DO 987 I=101,150
  987 READ(NR,304)(IDATE(I,K),K=1,3),(FALWTH(I,L),L=1,3)
       REWIND NR
      RETURN
      END
C
      SUBROUTINE PSYSUN(DB,WB,R,W,H,DP,SV,M)
C     SUBROUTINE AUTHOR--- TSENG-YOA SUN 1971
C     'HEATING,PIPING,& AIR CONDITIONING' ,43(10):98-100
C     PSYCHOMETRIC SUBROUTINE USES A.S.H.R.A.E. ALOGORITHMS
C----- FOR M=1, INPUT=DB,WB        OUTPUT=R,W,H,DP,SV
C----- FOR M=2, INPUT=DB,R         OUTPUT=WB,W,H,DP,SV
C----- FOR M=3, INPUT=DB,W         OUTPUT=WB,R,H,DP,SV
C----- FOR M=4, INPUT=DB,H         OUTPUT=WB,R,W,DP,SV
C----- FOR M=5, INPUT=DB,DP        OUTPUT=WB,R,W,H,SV
      DATA PB,FS/29.921,1.0045/
      GO TO(10,20,30,40,50),M
   10 PVP=PV(DB,WB,PB,FS)
      W=0.622*FS*PVP/(PB-FS*PVP)
      R=PVP/PVSF(DB)
      GO TO 15
   20 W=WF(DB,R,PB,FS)
      GO TO 25
   50 PVP=PVSF(DP)
      W=0.622*FS*PVP/(PB-FS*PVP)
      GO TO 30
   40 W=(H-0.24*DB)/(1061.+0.444*DB)
   30 R=RHF(DB,W,PB,FS)
   25 WB=WBF(DB,W,PB,FS)
      IF(M-5)15,45,15
   15 DP=DPF(DB,W,PB,FS)
      IF(M-4)45,55,45
   45 H=0.24*DB+(1061.+0.444*DB)*W
   55 R=R*100.
C  SPECIFIC VOLUME AT TEMPERATURE DB AND HUMIDITY RATIO W
      SV=(53.352*(459.67+DB)/(PB*70.7262))*(1.0+1.6078*W)
      RETURN
      END
C  SATURATED VAPOR PRESSURE AT TEMPERATURE DB
      FUNCTION PVSF(DB)
      DATA A,B,C/-7.90298,5.02808,-1.3816E-7/
      DATA D,E,F/11.344,8.1328E-3,-3.49149/
      DATA G,H,P,Q/-9.09718,-3.56654,0.876793,6.0273E-3/
      T=(DB+459.688)/1.8
      IF(T.LT.273.16)GO TO 3
```

```
      Z=373.16/T
      S=A*(Z-1.)+B*ALOG10(Z)+C*(10.**(D*(1.0-1.0/Z))-1.0)
      S=S+E*(10.**(F*(Z-1.))-1.)
      GO TO 4
    3 Z=273.16/T
      S=G*(Z-1.)+H*ALOG10(Z)+P*(1.-1./Z)+ALOG10(Q)
    4 PVSF=29.921*10.**S
      RETURN
      END
C   VAPOR PRESSURE AT TEMPERATURES DB AND WB
      FUNCTION PV(DB,WB,PB,FS)
      R=0.0
      PVS=PVSF(WB)
      IF(DB.LE.WB)GO TO 4
      WS=0.622*PVS/(PB-PVS)
      IF(WB.GT.32.0)GO TO 2
      PV=PVS-5.704E-4*PB*(DB-WB)/1.8
      GO TO 3
    4 PV=PVS
      GO TO 3
    2 CDB=(DB-32.0)/1.8
      CWB=(WB-32.0)/1.8
      HL=597.31+0.4409*CDB-CWB
      CH=0.2402+0.4409*WS
      EX=(WS-CH*(CDB-CWB)/HL)/0.622
      PV=PB*EX/1
      PV=PB*EX/(1.0+EX)
      IF(R.GT.0.0)GO TO 3
      R=PV/PVSF(DB)
      IF(R.GT.0.1)GO TO 3
      WS=0.622*FS*PVS/(PB-FS*PVS)
      GO TO 2
    3 RETURN
      END
C   HUMIDITY RATIO AT TEMPERATURE DB AND RELATIVE HUMIDITY R
      FUNCTION WF(DB,R,PB,FS)
      PVS=PVSF(DB)
      WS=0.622*FS*PVS/(PB-FS*PVS)
      R=R*0.01
      DS=R*(PB-FS*PVS)/(PB-R*FS*PVS)
      WF=WS*DS
      RETURN
      END
C   RELATIVE HUMIDITY AT TEMPERATURE DB AND HUMIDITY RATIO W
      FUNCTION RHF(DB,W,PB,FS)
      PVS=PVSF(DB)
      WS=0.622*FS*PVS/(PB-FS*PVS)
      DS=W/WS
      RHF=DS/(1.0-(1.0-DS)*FS*PVS/PB)
      RETURN
      END
C   WB TEMPERATURE AT TEMPERATURE DB AND HUMIDITY RATIO W
      FUNCTION WBF(DB,W,PB,FS)
      WBF=DB
      PVD=PB*W/((0.622+W)*FS)
   11 PVP=PV(DB,WBF,PB,FS)
      IF(PVP-PVD)20,30,10
   10 WBF=WBF-1.0
      GO TO 11
   20 WBH=WBF+1.0
```

```
      PVH=PV(DB.WBH.PB.FS)
      X=(PVD-PVP)/(PVH-PVP)
      WBF=WBH*X+WBF*(1.0-X)
   30 RETURN
      END
C   DP TEMPERATURE AT TEMPERATURE DB AND HUMIDITY RATIO W
      FUNCTION DPF(DB.W.PB.FS)
      DPF=DB
      PVD=PB*W/((0.622+W)*FS)
   11 PVS=PVSF(DPF)
      IF(PVS-PVD)20.30.10
   10 DPF=DPF-1.0
      GO TO 11
   20 DPH=DPF+1.0
      PVH=PVSF(DPH)
      X=(PVD-PVS)/(PVH-PVS)
      DPF=DPH*X+DPF*(1.0-X)
   30 RETURN
      END
C
      SUBROUTINE FALDRY
      COMMON/GRNDRY/GRNHAR(6.100.3).FALWTH(150.3).STORGR(6.20.7).
     *IPRT.SUPHET(6.2).IDATE(150.3).IFINSH.FMTA.FMTM.GRMSTA.
     *BIN(6.4).HEAADD.CUMKWH.FANHRS.ICOUNT.ISTIR.CFMPB.
     *NB.NY.IDAY.ISDAY.IFANON.LAYER.MAXLAY.RH.LPRINT.PR
      FANHRS=0.0
      CUMKWH=0.0
      IDAY=1
      IFANON=0
      IFINSH=0
      PR=0.0
      ICOUNT=0
      ISTIR=1
      IF(BIN(NB.4).EQ.0.0) ISTIR=0
      IF(BIN(NB.4).EQ.-2.0) ISTIR=0
   10 IF(GRNHAR(NB.IDAY.1).GT.1.) GO TO 15
       IF(IDAY.EQ.100) RETURN
      IDAY=IDAY+1
      GO TO 10
   15 IF(IFINSH.EQ.1) GO TO 21
      IF(GRNHAR(NB.IDAY.1).LT.1.) GO TO 20
      IFANON=1
      DO 12 LAYER=1.MAXLAY
      STORGR(NB.LAYER.1)= GRNHAR(NB.ISDAY.3)
      STORGR(NB.LAYER.2)= GRNHAR(NB.ISDAY.2)
      STORGR(NB.LAYER.7)=(STORGR(NB.LAYER.2)/(100.-STORGR(NB.LAYER.2)))
     * *100.
      STORGR(NB.LAYER.3)=STORGR(NB.LAYER.7)
   12 CONTINUE
      GO TO 21
   20 IF(GRNHAR(NB.IDAY.1).EQ.-1.0) IFINSH = 1
   21 IPRT = 0
      IF(IFANON.EQ.0) GO TO 18
       IF(LPRINT .LT. 1) GO TO 17
         IF(IDAY.EQ.27) IPRT=1
         IF(IDAY.EQ.41) IPRT=1
         IF(IDAY.EQ.55) IPRT=1
         IF(IDAY.EQ.69) IPRT=1
         IF(IDAY.EQ.83) IPRT=1
         IF(IDAY.EQ.101)IPRT=1
```

```
            IF(IDAY.EQ.115)IPRT=1
            IF(IDAY.EQ.129)IPRT=1
            IF(IDAY.EQ.143)IPRT=1
          IF(LPRINT .LT. 2) GO TO 17
            IF(IDAY.EQ.20) IPRT=1
            IF(IDAY.EQ.34) IPRT=1
            IF(IDAY.EQ.48) IPRT=1
            IF(IDAY.EQ.62) IPRT=1
            IF(IDAY.EQ.76) IPRT=1
            IF(IDAY.EQ.90) IPRT=1
            IF(IDAY.EQ.108)IPRT=1
            IF(IDAY.EQ.122)IPRT=1
            IF(IDAY.EQ.136)IPRT=1
          IF(LPRINT .LT. 3) GO TO 17
          IPRT=1
 17     CONTINUE
        IF(IPRT.EQ.1) CALL PRINT
 18     IF(IDAY.EQ.150) RETURN
        IDAY=IDAY+1
        IF(IFANON.EQ.0) GO TO 24
        CALL VANCE
 24     IF(IFANON.EQ.0.AND.IFINSH.EQ.1) RETURN
 25     IF(IDAY.LT.150) GO TO 15
        RETURN
        END
 C
        SUBROUTINE PRINT
        COMMON/GRNDRY/GRNHAR(6,100,3),FALWTH(150,3),STORGR(6,20,7),
       $IPRT,SUPHET(6,2),IDATE(150,3),IFINSH,FMTA,FMTM,GRMSTA,
       $BIN(6,4),HEAADD,CUMKWH,FANHRS,ICOUNT,ISTIR,CFMPB,
       $NB,NY,IDAY,ISDAY,IFANON,LAYER,MAXLAY,RH,LPRINT,PR
        REAL AVG(5)
        JYR  =NY+50
        DO 40 II=1,5
        AVG(II) =0.0
        DO 30 KK=1,MAXLAY
        AVG(II)=AVG(II)+STORGR(NB,KK,II)/FLOAT(MAXLAY)
  30    CONTINUE
  40    CONTINUE
        IDAYKK=IDAY
        IF(IDAY.GT.100)IDAYKK=100
        WRITE(6,100)(IDATE(IDAY,KI),KI=1,3),(FALWTH(IDAY,KJ),KJ=1,2),
       1IFANON,NB,CFMPB,BIN(NB,2),FANHRS,BIN(NB,1),
       1CUMKWH,HEAADD,GRNHAR(NB,ISDAY,1),MAXLAY,
       2GRNHAR(NB,ISDAY,2),BIN(NB,4),ISTIR
  100   FORMAT('1'/'0'/'0',10X,'DATE/PLACE....',A4,'/ ',A4,'/ ',A4/'0',
       110X,'AVERAGE TEMP. (F) ',F6.1/'0',10X,'AVERAGE REL. HUM. '
       2,F5.1//'0',
       1'FAN (0=OFF 1=ON).....',I8  ,T61,'BIN NUMBER.........',I6/'0',
       2'AIR FLOW (CFM/BU)....',F8.2,T61,'FAN POWER (KW).....',F6.2/'0',
       3'FAN HOURS ...........',F8.1,T61,'BIN DIAMETER (FT).',F6.1/'0',
       4'KWHS USED............',F8.1,T61,'TEMP RISE (DEG F).',F6.2/'0',
       5'TOTAL BUSHELS IN BIN.',F8.1,T61,'NO. OF LAYERS.....',I6/'0',
       6'INITIAL MOISTURE (WB)',F8.1,T61,'STIRRING OPTION...',F6.1/'0',
       7'TIMES STIRRED........',I8)
        WRITE(6,101) (STORGR(NB,I,2),I=1,20),
       1(STORGR(NB,K,1),K=1,20),(STORGR(NB,L,5),L=1,20)
  101   FORMAT(' '/'0'/'0','GRAIN MOISTURE-PERCENT WET BASE'/'0',20F6.1/'0
       1','GRAIN TEMPERATURE-DEGREES FAHRENHEIT'/'0',20F6.1/'0',
       2'CUMULATIVE GRAIN DETERIORATION-PEPCENT OF DRY MATTER'/'0',
```

```
     320F6.3)
      WRITE(6.102)AVG(2).AVG(3).AVG(1).AVG(5)
  102 FORMAT(' '/'0'/'0'.'AVERAGE GRAIN MOISTURE(PERCENT)'/' MCWB='.F6.1
     1.'    MCDB='.F6.1/'0'.'AVERAGE TEMP(F)='.F6.2/'0'.'AVERAGE DETERIOR
     2ATION(PERCENT)='.F6.3)
       IPRT=0
      RETURN
      END
C
      SUBROUTINE FINPRT(IU)
      COMMON/GRNDRY/GRNHAR(6.100.3).FALWTH(150.3).STORGR(6.20.7).
     *IPRT.SUPHET(6.2).IDATE(150.3).IFINSH.FMTA.FMTM.GRMSTA.
     *BIN(6.4 ).HEAADD.CUMKWH.FANHRS.ICOUNT.ISTIR.CFMPB.
     *NB.NY.IDAY.ISDAY.IFANON.LAYER.MAXLAY.RH.LPRINT.PR
      IYRMOD=1950+NY
      GRMSTM=STORGR(NB.1.2)
      LAYMXM=1
      DETMAX=STORGR(NB.1.5)
      LAYMXD=1
      DO 10 I=2.MAXLAY
      IF(STORGR(NB.I.5).LT.DETMAX)GO TO 8
      LAYMXD=I
      DETMAX=STORGR(NB.I.5)
    8 IF(STORGR(NB.I.2).LT.GRMSTM)GO TO 10
      LAYMXM=I
      GRMSTM=STORGR(NB.I.2)
   10 CONTINUE
   20 GRTEMP=0.
      GRMSTA=0.
      DETAVG=0.
      DO 15 J=1.MAXLAY
      GRTEMP=GRTEMP+STORGR(NB.J.1)/FLOAT(MAXLAY)
      GRMSTA=GRMSTA+STORGR(NB.J.2)/FLOAT(MAXLAY)
      DETAVG=DETAVG+STORGR(NB.J.5)/FLOAT(MAXLAY)
   15 CONTINUE
      WRITE(IU.100)IYRMOD.GRNHAR(NB.ISDAY.1).NB.(IDATE(IDAY.KI).KI=1.2).
     *FANHRS.CUMKWH.GRMSTA.GRMSTM.LAYMXM.DETAVG.DETMAX.LAYMXD.GRTEMP.
     *CFMPB.HEAADD.BIN(NB.1).BIN(NB.2).BIN(NB.4).ISTIR.
     *GRNHAR(NB.ISDAY.2)
  100 FORMAT(' '.I4.F7.0.2X.I2.1X.2A4.F7.0.F8.0.2F5.1.2X.I2.1X.2F6.2.
     *1X.I2.3X.F5.1.2X.F5.2.F5.1.F4.0.F6.2.2X.F4.1.2X.I3.F9.2)
      RETURN
      END
C
      SUBROUTINE VANCE
      COMMON/GRNDRY/GRNHAR(6.100.3).FALWTH(150.3).STORGR(6.20.7).
     *IPRT.SUPHET(6.2).IDATE(150.3).IFINSH.FMTA.FMTM.GRMSTA.
     *BIN(6.4).HEAADD.CUMKWH.FANHRS.ICOUNT.ISTIR.CFMPB.
     *NB.NY.IDAY.ISDAY.IFANON.LAYER.MAXLAY.RH.LPRINT.PR
      DIMENSION T(21).H(21)
      COMMON/EQZ/C.GCI.TCI.HCI.DELL.IRW.DMCI.R.QFAN.TIJ
      EXTERNAL EQZERO
C
C  AIRFLOW MODIFICATION EQUATIONS
C
      IF(BIN(NB.4).LT.0.0) AR=1.0
      IF(BIN(NB.4).EQ.0.0) AR=1.0-0.01005*PR+0.00233*(PR**2)
      IF(BIN(NB.4).EQ.1.0) AR=1.0-0.00535*PR-0.00109*(PR**2)
      IF(BIN(NB.4).EQ.2.0) AR=1.0-0.0470*PR +0.00401*(PR**2)
      CFMPB=BIN(NB.3)*AR
```

```
      CFM=CFMPB*GRNHAR(NB,ISDAY,1)
      AIRLBS=CFM/12.75
C
C  TEMP. RISE BASED ON (1-FME)*ELECTRICAL POWER INPUT TO FAN
C  FME=IMPELLER EFFICIENCY * MOTOR EFFICIENCY
      FME=0.425
      BTU=BIN(NB,2)*56.90*(1.0-FME) + SUPHET(NB,1)
      HEAADD=(BTU/AIRLBS/0.24) + SUPHET(NB,2)
       AIRDRY=HEAADD+FALWTH(IDAY,1)
      DRMTBU=47.32
      HUMKK   = FALWTH(IDAY,3)
       ABSTEM=460.+AIRDRY
       ATMP=14.696
       DT=24
      VAPPRE=HUMKK  *ATMP/(HUMKK  +.622)
      DENAIR=144*(ATMP-VAPPRE)/(53.35* ABSTEM)
C
C  ONLY 74% OF INPUT AIRFLOW IS EFFECTIVE IN DRYING
      R = DRMTBU /(CFMPB * 0.74 * 60.0 * DT * DENAIR * MAXLAY)
C
C  REMAINING FAN HEAT IS IGNORED
      QFAN = 0.0
      T(1)=AIRDRY
      H(1)=HUMKK
      RH = RHS(HUMKK  ,AIRDRY )
      IF(RH.GE.1.)  RH = .99
      XEMC =  SQRT((-ALOG(1.-RH))/(.0000382*(AIRDRY +50.0)))
C           DO LOOP *40* IS THE BEGINNING OF THE LAYER ANALYSIS.
      DO 40 I = 1, MAXLAY
      IJ=I+1
      C=((.35+.00851*STORGR(NB,I,2))*R)/(1.-STORGR(NB,I,2)/100.)
      N = 0
      HF=HUMKK
      DELL=(1094.-.57*T(I))*4.35 * EXP(-28.25 * STORGR(NB,I,3)/100.0)
C           WHEN IRW = 0   DRYING
C           WHEN IRW = 1   REWETTING
C           WHEN IRW = 2   HYSTERESIS
       IRW = 0
       RHA = RHS(H(I),T(I))
       IF(RHA.GE.1.)  RHA = .99
       ERHD = 1.-EXP(-3.82E-5*(T(I)+50.0)*STORGR(NB,I,3)**2)
       IF(RHA.LT.ERHD)  GO TO 200
       ERHW = 1.-EXP(-1.045E-4*(T(I)+50.0)*STORGR(NB,I,3)**1.72)
       IF(RHA.GT.ERHW)  GO TO 199
       XMI = STORGR(NB,I,3)
       HF = H(I)
       IRW = 2
       GO TO 198
  199  CONTINUE
       IRW = 1
  200  CONTINUE
       IF(IRW.EQ.1)  GO TO 1201
       AA = H(I)
       BB  = H(I) + .001
       GO TO 1202
 1201  CONTINUE
       BB = H(I)
       AA = H(I) - .001
 1202  CONTINUE
       GC1 = STORGR(NB,I,1)
```

```
      TC1 = T(I)
      HC1 = H(I)
      DMC1 = STORGR(NB,I,3)
      CALL ZEROUT(AA, BB, .000005, EQZERO)
      HF = (AA + BB) / 2.0
      XMI = STORGR(NB,I,3) - 100*(HF - H(I)) / R
      T(IJ) = (C*STORGR(NB,I,1) + .24*T(I) + .45*H(I)*T(I) + QFAN
     $-((HF-H(I))*(1060.8+32.-STORGR(NB,I,1)+DELL)))/(.24+.45*HF+C)
C          IF THE THIN LAYER EQUATION IS BYPASSED, GO TO *60* FROM HERE.
      IF(IRW.EQ.1)  GO TO 60
      CM1=ABS(STORGR(NB,I,3)-XMI)
      IF(CM1.LT..0001) GO TO 60
      XMC=STORGR(NB,I,3)
      CALLTHLYLT(XMC,T(I),H(I),DT,STORGR(NB,I,7),KAB,RH1,XME1,TXMO1,
     * I,RHA,IRW)
      CM2=ABS(STORGR(NB,I,3)-XMC)
      IF(CM1.LT.CM2) GO TO 60
      XMI=XMC
      HF=H(I)+0.01*R*(STORGR(NB,I,3)-XMI)
  198 CONTINUE
      T(IJ) = (C*STORGR(NB,I,1) + .24*T(I) + .45*H(I)*T(I) + QFAN
     $-((HF-H(I))*(1060.8+32.-STORGR(NB,I,1)+DELL)))/(.24+.45*HF+C)
   60 CONTINUE
      STORGR(NB,I,3) = XMI
      STORGR(NB,I,2)=(100.*STORGR(NB,I,3))/(100.+STORGR(NB,I,3))
      STORGR(NB,I,1)=T(IJ)
      H(IJ)=HF
       STORGR(NB,I,6)=STORGR(NB,I,6) + (DT*230.)/
     *  (SAFES(STORGR(NB,I,1),STORGR(NB,I,2)))
      STORGR(NB,I,5)=.0884 *(EXP(.006*STORGR(NB,I,6))-1.)+.00102*
     *  STORGR(NB,I,6)
40    CONTINUE
       FANHRS=FANHRS+DT
      DAYENG=DT*(BIN(NB,2)+0.01758*SUPHET(NB,I))
      CUMKWH=CUMKWH+DAYENG
C
C     LOGIC FOR BIN SHUT DOWN
C
      GRMSTA=0.0
      GRMSTM=0.0
      GRTMAX=0.0
      DO 310 I=1,MAXLAY
      GRMSTA=GRMSTA+STORGR(NB,I,2)/FLOAT(MAXLAY)
310   IF(STORGR(NB,I,2).GT.GRMSTM)GRMSTM=STORGR(NB,I,2)
      PR=GRNHAR(NB,ISDAY,2)-GRMSTA
      IF(BIN(NB,4).LE.0.0) GO TO 320
      IF(GRMSTA.LE.FMTA) GO TO 319
      IF(BIN(NB,4).EQ.1.0) GO TO 315
      ICOUNT=ICOUNT + 1
      IF(ICOUNT.EQ.7) GO TO 319
      GO TO 320
315   IF(GRNHAR(NB,ISDAY,2).LT.21.0.OR.ISTIR.EQ.2) GO TO 320
      IF(GRMSTA.GT.20.0) GO TO 320
319   CALL STIR
      GRMSTM=GRMSTA
320   DO 330 I=1,MAXLAY
330   IF(STORGR(NB,I,1).GT.GRTMAX)GRTMAX=STORGR(NB,I,1)
      IF(IDAY.EQ.100) IFINSH=1
      IF(IFINSH.EQ.1) GO TO 300
      IF(GRMSTA.GT.FMTA.OR.GRMSTM.GT.FMTM) RETURN
```

```
      CALL FINPRT(1)
      IFANON = 0
      RETURN
  300 IF(GRMSTA.LT.FMTA.AND.GRMSTM.LT.FMTM) GO TO 360
      IF(IDAY.EQ.100) GO TO 350
      IF(IDAY.EQ.150) GO TO 360
      IF(IDAY.LT.69.OR.IDAY.GT.100) RETURN
      IF(GRTMAX.GE.30.)RETURN
      IF(STORGR(NB.MAXLAY.2).LT.18.) GO TO 350
      IF(GRTMAX.GT.25.)RETURN
      IF(IDAY.LT.85)RETURN
      IF(STORGR(NB.MAXLAY.2).LT.20.)GO TO 350
      IF(GRTMAX.GE.20.)RETURN
  350 IFANON=0
      STRTIM=(105+100-IDAY)*24.
      IF(LPRINT.GE.0) CALL PRINT
      CALL FINPRT(1)
      DO 355 I=1.MAXLAY
      STORGR(NB.I.6)=STORGR(NB.I.6) + (STRTIM*230.)/
     *(SAFES(STORGR(NB.I.1).STORGR(NB.I.2)))
      STORGR(NB.I.5)=.0884*(EXP(.006*STORGR(NB.I.6))-1.)
     *+.00102*STORGR(NB.I.6)
  355 CONTINUE
      IF(NY.GE.33) CALL FINPRT(3)
      IF(NY.GE.33) RETURN
      IFANON=1
      IDAY=100
      RETURN
  360 IFANON=0
      IF(LPRINT.GE.0)CALL PRINT
      IF(IDAY.LT.100) CALL FINPRT(1)
      CALL FINPRT(3)
      RETURN
      END
C
      SUBROUTINE STIR
      COMMON/GRNDRY/GRNHAR(6.100.3).FALWTH(150.3).STORGR(6.20.7).
     *1PRT.SUPHET(6.2).IDATE(150.3).IFINSH.FMTA.FMTM.GRMSTA.
     *BIN(6.4).HEAADD.CUMKWH.FANHRS.ICOUNT.ISTIR.CFMPB.
     *NB.NY.IDAY.ISDAY.IFANON.LAYER.MAXLAY.RH.LPRINT.PR
      ISTIR=ISTIR+1
      ICOUNT=0
      DBMCA=(GRMSTA/(100.-GRMSTA))*100.
      AVGT=0.0
      AVGD=0.0
      DO 100 I=1.MAXLAY
      AVGT=AVGT+STORGR(NB.I.1)/FLOAT(MAXLAY)
  100 AVGD=AVGD+STORGR(NB.I.5)/FLOAT(MAXLAY)
      DO 110 I=1.MAXLAY
      STORGR(NB.I.1)=AVGT
      STORGR(NB.I.2)=GRMSTA
      STORGR(NB.I.3)=DBMCA
  110 STORGR(NB.I.5)=AVGD
      RETURN
      END
C
      FUNCTIONSAFES(T.WB)
      W=WB
      IF(W .LE. 1)W=W*100.
      DM=1.0
```

```
      TR=230.0
      DB=W/(100.-W)*100.
      XMM=.103*(EXP(455./DB**1.53)-.00845*DB+1.558)
      IF(T-60.)10.20.20
 10   XMT=128.76*EXP(-.081*T)
      GOTO70
 20   IF(W-19.)30.30.40
 30   W=19.
 40   IF(W-28.)60.60.50
 50   W=28.
 60   XMT=32.3*EXP(-3.48*T/60.)+(W-19.)*.01*EXP(.61*(T-60.)/60.)
 70   SAFES=TR*XMM*XMT*DM
      RETURN
      END
C       ************************************************************
C       FUNCTION EQZERO     02/27/76
      FUNCTION EQZERO(HF)
      COMMON/EQZ/C.G.T.H.DELL.IRW.DM.R.QFAN.TIJ
      XMI = DM - 100.0 *(HF - H)/ R
      TIJ = (C*G + .24 * T + .45*H*T + QFAN
     $ -((HF - H)*(1060.8 + 32.0 - G + DELL)))/(.24 + .45*HF + C)
      IF(XMI.LT..001)  XMI = .001
      IF(IRW.EQ.1)  GO TO 1190
      ERH = 1. - EXP(-3.82E-5*(TIJ + 50.0) * XMI**2)
      GO TO 1191
 1190 CONTINUE
      ERH = 1. - EXP(-1.045E-4*(TIJ+ 50.0) * XMI**1.72)
 1191 CONTINUE
      RHSS = RHS(HF.TIJ)
      EQZERO = ERH - RHSS
      RETURN
      END
C        ***********************************************************
      FUNCTION PSDB (DB)
      DOUBLE PRECISION R.A.B.C.D.E.F.G
      REAL*8 DEXP
      DATA R.A.B.C.D.E.F.G/.3206182232D04.-.2740552583614 26D05..54189607
     A6328951D02.-.4513703841126550-1..21532119163635 4D-4.-.462026656819
     89820-8..24161272098 74D01..12154651670605 5D-2/
      IF(DB-491.69) 1.2.2
    1 PSDB= EXP(23.3924-11286.64  /DB-.46057*ALOG(DB))
      RETURN
    2 PSDB=R*DEXP((A+DB*(B+DB*(C+DB*(D+DB*E))))/(DB*(F-G*DB)))
      RETURN
      END
C         **********************************************************
C        RHS SUBPROGRAM
      FUNCTION RHS(H. TS)
      T = TS + 459.69
      PS = PSDB(T)
      RHS = (14.696*H/(H + 0.6219))/ PS
      RETURN
      END
C         **********************************************************
C           SUBROUTINE ZEROUT
      SUBROUTINE ZEROUT(A. B. EPS. FUNC)
C      UPDATE 8/17/76.
C            RANGE SELECTOR ADDED.
      REAL I. M
      IC = 0
```

```
            D = B - A
         20 CONTINUE
            IF(IC.GE.20)  GO TO 30
            FA = FUNC(A)
            FB = FUNC(B)
            FC = FA
            C = A
            IF(SIGN(1..FB).NE.SIGN(1..FC)) GO TO 1
            IC = IC + 1
            IF(ABS(FA).GT.ABS(FB))  GO TO 21
            B = A + (2*EPS)
            A = A - D
            GO TO 20
         30 CONTINUE
            WRITE(6.100) IC. A. B. FA. FB
        100 FORMAT(1X.'ZEROUT CANT FIND A RANGE IN '.I2.' ITERATIONS.  LIMITS
           $='.2F12.6.' FUNCTION VALUES = '.2F12.6)
            RETURN
         21 CONTINUE
            A = B - (2*EPS)
            B = B + D
            GO TO 20
          1 IF(ABS(FC) - ABS(FB)) 2. 3. 3
          2 C = B
            B = A
            A = C
            FC = FB
            FB = FA
            FA = FC
          3 IF(ABS(C - B) - 2. * EPS)  12. 12. 4
  4         M = (C + B) / 2.0
            DIV=FB-FA
            IF(DIV.EQ.0.) GO TO 7
            CALL OVERFL(IREG)
            I=(B-A)*FB/DIV
            CALL OVERFL(IREG)
            IF (IREG.NE.2) GO TO 7
          5 I = -I + B
            CHINT = (B - I) * (M - I)
            IF(CHINT) 8. 8. 7
          7 I = M
          8 IF(ABS(B - I) - EPS) 9. 10. 10
          9 I = SIGN(1..(C - B)) * EPS + B
         10 A = B
            B = I
            FA = FB
            FB = FUNC(B)
            IF(SIGN(1..FB) - SIGN(1..FC)) 1.  11. 1
         11 C = A
            FC = FA
            GO TO 1
         12 A = (C + B) / 2.0
            FA = FUNC(A)
            IF(SIGN(1..FA).EQ.SIGN(1..FB))  B = C
            RETURN
            END
  C              ****************************************************************
  C
            SUBROUTINE THLYLT(XMC.TH.HA.DELT.XMO.KAB.RH.XME.TXMO.I.RHA.IRW)
            DIMENSION TGUESS(50)
```

```
      DATA TGUESS/50*1.0/
      RH = RHA
      XME=SQRT((-ALOG(1.-RH))/(.0000382*(TH+50.)))
      IF(XME.LT.XMC) GO TO 12
      WRITE(6.1090)  XMC.XME. IRW. TH. RH
 1090 FORMAT(1X.'POSSIBLE ERROR IN THLYLT. VARIALBES '.2F8.4.I5.2F8.4)
   12 IF(XMO.LT.XMC) GO TO 13
      TXMO=XMO
      GO TO 15
   13 TXMO=XMC
   15 DELM=TXMO-XME
      XMR=(XMC-XME)/DELM
C*****
C*****   EQUATIONS TO FIND MOISTURE CONTENT BY M.A. SABBAH
C*****
  101 RSQ=RH*RH
      X=SQRT(6.0142+1.453*RSQ)-0.01*TH*SQRT(3.353+3.*RSQ)
      Y=0.1245-0.22*RH+0.0023*RH*TH-0.000058*TH
      K=0
      T1=TGUESS(I)
C*****   CHECK IF DERIVATIVE IS VERY LARGE...IF IT IS ASSIGN T2=0.0
      IF(XMR.LT..999) GO TO 102
      T2=0.0
      GOTO 104
  102 U=ALOG(-ALOG(XMR))
C*****   NEWTON-RAPHSON TECHNIQUE TO FIND EQUIVALENT TIME
  103 Z1=X*T1**Y-.664*ALOG(T1)+U
      Z2=X*Y*T1**(Y-1.)-.664/T1
      T2=T1-Z1/Z2
      K=K+1
      EPS=ABS(T2-T1)
      IF(T2.LT.0.0) T2=0.0010
      T1=T2
      IF(K.LT.20) GO TO  300
      WRITE(6.150) K
      WRITE(6.301)T2.T1.Z1.Z2.X.Y.U.XMR
  301 FORMAT(10F12.4)
      STOP
  300 CONTINUE
  150 FORMAT(33H0THE METHOD HAS NOT CONVERGED IN . I2.11H ITERATIONS)
      IF(EPS.GT..01.OR.Z1.GT..01) GO TO 103
C*****   ADD DELT TO EQUILVALENT TIME. SOLVE FOR NEW M AND RETURN
  104 T2=T2+DELT
      TGUESS(I)=T2
      XMC=DELM*EXP(-EXP(-X*T2**Y)*T2**.664)+XME
      RETURN
      END
//GO.FT01F001  DD  SYSOUT=A.DCB=(RECFM=FBA.LRECL=133.BLKSIZE=133)
//GO.FT03F001  DD  SYSOUT=A.DCB=(RECFM=FBA.LRECL=133.BLKSIZE=133)
//GO.FT04F001  DD  SYSOUT=A.DCB=(RECFM=FBA.LRECL=133.BLKSIZE=133)
//GO.FT13F001  DD  DSN=W.I3463.DLIB(DM63).DISP=SHR
//GO.FT14F001  DD  DSN=W.I3463.DLIB(DM64).DISP=SHR
//GO.FT15F001  DD  DSN=W.I3463.DLIB(DM65).DISP=SHR
//GO.FT16F001  DD  DSN=W.I3463.DLIB(DM66).DISP=SHR
//GO.FT17F001  DD  DSN=W.I3463.DLIB(DM67).DISP=SHR
//GO.FT18F001  DD  DSN=W.I3463.DLIB(DM68).DISP=SHR
//GO.FT19F001  DD  DSN=W.I3463.DLIB(DM69).DISP=SHR
//GO.FT20F001  DD  DSN=W.I3463.DLIB(DM70).DISP=SHR
//GO.FT21F001  DD  DSN=W.I3463.DLIB(DM71).DISP=SHR
//GO.FT22F001  DD  DSN=W.I3463.DLIB(DM72).DISP=SHR
```

```
//GO.FT23F001  DD  DSN=W.I3463.DLIB(DM73),DISP=SHR
//GO.FT24F001  DD  DSN=W.I3463.DLIB(DM74),DISP=SHR
//GO.FT25F001  DD  DSN=W.I3463.DLIB(DM75),DISP=SHR
//GO.FT26F001  DD  DSN=W.I3463.DLIB(DM76),DISP=SHR
//GO.FT27F001  DD  DSN=W.I3463.DLIB(DM77),DISP=SHR
//GO.FT28F001  DD  DSN=W.I3463.DLIB(DM78),DISP=SHR
//GO.FT29F001  DD  DSN=W.I3463.DLIB(DM79),DISP=SHR
//GO.FT30F001  DD  DSN=W.I3463.DLIB(DM80),DISP=SHR
//GO.FT31F001  DD  DSN=W.I3463.DLIB(DM81),DISP=SHR
//GO.FT32F001  DD  DSN=W.I3463.DLIB(DM82),DISP=SHR
//GO.FT33F001  DD  DSN=W.I3463.DLIB(DM83),DISP=SHR
//GO.SYSIN  DD  *
/*
```

SUMMARY OF SIMULATED DRYER RESULTS
FINAL SHUT DOWN CONDITIONS

YEAR	BUSHELS	BIN NO.	FAN OFF	FAN HOURS	KWHS USED	GRAIN MOISTURE AVG	MAX	LAYER	DETERIORATION AVG	MAX	LAYER
1963	2428.	1	6311 6	528.	7920.	12.8	14.9	10	0.47	0.75	10
1963	2925.	2	6312 3	1176.	4234.	15.5	15.5	10	0.68	0.68	10
1964	2428.	1	6411 8	576.	8640.	14.2	15.3	10	0.14	0.32	10
1964	2925.	2	65 426	1752.	6307.	15.5	15.5	10	0.40	0.40	10
1965	2428.	1	6511 5	504.	7560.	12.4	15.2	10	0.25	0.39	10
1965	2925.	2	6512 8	1296.	4666.	15.5	15.5	10	0.38	0.38	10
1966	2428.	1	6611 4	480.	7200.	12.1	15.0	10	0.07	0.14	10
1966	2925.	2	67 4 7	1296.	4666.	15.5	15.5	10	0.16	0.16	10
1967	2428.	1	6711 5	504.	7560.	13.4	15.3	10	0.07	0.15	10
1967	2925.	2	671128	1056.	3802.	15.4	15.4	10	0.13	0.13	10
1968	2428.	1	6811 7	552.	8280.	13.3	15.1	10	0.14	0.26	10
1968	2925.	2	69 411	1536.	5530.	15.4	15.4	10	0.27	0.27	10
1969	2428.	1	6911 9	600.	9000.	13.3	14.9	10	0.09	0.17	10
1969	2925.	2	6912 1	1128.	4061.	15.4	15.4	10	0.16	0.16	10
1970	2428.	1	7011 9	600.	9000.	13.7	15.3	10	0.18	0.35	10
1970	2925.	2	7012 5	1224.	4406.	15.3	15.3	10	0.30	0.30	10
1971	2428.	1	711111	648.	9720.	13.3	15.0	10	0.40	0.75	10
1971	2925.	2	72 410	1656.	5962.	15.5	15.5	10	0.75	0.75	10
1972	2428.	1	73 410	984.	14760.	14.4	15.4	10	0.14	0.30	10
1972	2925.	2	73 426	1800.	6480.	15.4	15.4	10	0.40	0.40	10
1973	2428.	1	7311 4	480.	7200.	13.1	15.3	10	0.15	0.32	10
1973	2925.	2	74 4 4	1320.	4752.	15.5	15.5	10	0.31	0.31	10
1974	2428.	1	7411 3	456.	6840.	13.7	15.4	10	0.13	0.36	10
1974	2925.	2	75 4 8	1344.	4838.	15.5	15.5	10	0.31	0.31	10
1975	2428.	1	7511 3	456.	6840.	13.2	15.3	10	0.12	0.26	10
1975	2925.	2	7512 6	1248.	4493.	15.4	15.4	10	0.30	0.30	10
1976	2428.	1	7611 9	600.	9000.	12.4	14.9	10	0.05	0.12	10
1976	2925.	2	761126	1008.	3629.	15.4	15.4	10	0.09	0.09	10
1977	2428.	1	771110	624.	9360.	14.1	15.4	10	0.19	0.46	10
1977	2925.	2	78 4 6	1368.	4925.	15.4	15.4	10	0.45	0.45	10
1978	2428.	1	7811 5	504.	7560.	12.8	15.4	10	0.13	0.27	10
1978	2925.	2	79 414	1488.	5357.	15.4	15.4	10	0.26	0.26	10
1979	2428.	1	7911 7	552.	8280.	13.2	15.1	10	0.26	0.44	10
1979	2925.	2	80 4 7	1296.	4666.	15.4	15.4	10	0.44	0.44	10
1980	2428.	1	8011 7	552.	8280.	12.2	14.3	10	0.11	0.19	10
1980	2925.	2	801122	912.	3283.	15.5	15.5	10	0.17	0.17	10
1981	2428.	1	8111 6	528.	7920.	13.2	15.4	10	0.11	0.26	10
1981	2925.	2	811128	1056.	3802.	15.4	15.4	10	0.23	0.23	10
1982	2428.	1	8211 6	528.	7920.	13.1	15.3	10	0.12	0.25	10
1982	2925.	2	83 415	1680.	6048.	15.5	15.5	10	0.25	0.25	10

GRAIN TEMP	CFM/BU	TEMP RISE	BIN DIA	FAN KW	STIR OPT.	TIMES STIRRED	MCI
53.1	3.27	3.3	18.	15.00	0.0	0	24.00
30.8	1.40	1.5	18.	3.60	1.0	3	24.00
57.5	3.16	3.4	18.	15.00	0.0	0	24.00
46.5	1.40	1.5	18.	3.60	1.0	3	24.00
54.6	3.36	3.2	18.	15.00	0.0	0	24.00
36.6	1.40	1.5	18.	3.60	1.0	3	24.00
36.7	3.38	3.2	18.	15.00	0.0	0	24.00
47.0	1.41	1.5	18.	3.60	1.0	3	24.00
30.9	3.22	3.3	18.	15.00	0.0	0	24.00
24.3	1.40	1.5	18.	3.60	1.0	3	24.00
41.5	3.24	3.3	18.	15.00	0.0	0	24.00
50.6	1.41	1.5	18.	3.60	1.0	3	24.00
54.7	3.22	3.3	18.	15.00	0.0	0	24.00
36.5	1.40	1.5	18.	3.60	1.0	3	24.00
53.5	3.21	3.3	18.	15.00	0.0	0	24.00
32.4	1.40	1.5	18.	3.60	1.0	3	24.00
49.3	3.21	3.3	18.	15.00	0.0	0	24.00
48.0	1.41	1.5	18.	3.60	1.0	3	24.00
31.6	3.12	3.4	18.	15.00	0.0	0	24.00
51.4	1.41	1.5	18.	3.60	1.0	3	24.00
38.0	3.25	3.3	18.	15.00	0.0	0	24.00
40.7	1.41	1.5	18.	3.60	1.0	3	24.00
46.9	3.19	3.4	18.	15.00	0.0	0	24.00
40.7	1.40	1.5	18.	3.60	1.0	3	24.00
66.2	3.28	3.3	18.	15.00	0.0	0	24.00
33.3	1.41	1.5	18.	3.60	1.0	3	24.00
44.8	3.31	3.2	18.	15.00	0.0	0	24.00
37.4	1.41	1.5	18.	3.60	1.0	3	24.00
37.8	3.13	3.4	18.	15.00	0.0	0	24.00
54.5	1.41	1.5	18.	3.60	1.0	3	24.00
59.0	3.26	3.3	18.	15.00	0.0	0	24.00
47.1	1.41	1.5	18.	3.60	1.0	3	24.00
37.1	3.26	3.3	18.	15.00	0.0	0	24.00
53.8	1.41	1.5	18.	3.60	1.0	3	24.00
57.9	3.34	3.2	18.	15.00	0.0	0	24.00
40.5	1.41	1.5	18.	3.60	1.0	3	24.00
47.6	3.18	3.4	18.	15.00	0.0	0	24.00
32.8	1.40	1.5	18.	3.60	1.0	3	24.00
42.2	3.25	3.3	18.	15.00	0.0	0	24.00
36.5	1.41	1.5	18.	3.60	1.0	3	24.00