DESIGN OF A PILOT-SCALE CONCURRENT FLOW GRAIN DRYER

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DENNIS PETER KLINE

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ABSTRACT

DESIGN OF A PILOT-SCALE CONCURRENT
FLOW GRAIN DRYER

By

Dennis Peter Kline

A continuous flow pilot-scale grain dryer with concurrent drying and counter-flow cooling was designed, constructed and tested. The dryer constitutes an evolution of previously designed models. Mechanical air locks and spreading devices have been eliminated. A positive grain metering mechanism has been installed to obtain consistent grain throughput rates.

The main body of the thesis details the construction and operation of the pilot-scale dryer used. Corn was used to test the dryer initially. After modification of the dryer, soybeans were dried.

Approved F. W. Bakker-Arkema
Major Professor

Approved D. R. Heldman
Department Chairman

DESIGN OF A PILOT-SCALE CONCURRENT FLOW GRAIN DRYER

By

Dennis Peter Kline

A THESIS

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I would like to thank Dr. Lynn S. Robertson and Lloyd E. Lerew for serving on my guidance committee and for the knowledge I gained from them while completing my program.

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The pilot-scaled dryer was designed, constructed, and tested jointly with my good friend, Stephen J. Kalchik. I would especially like to thank Stephen and my many friends at Michigan State University for their help and encouragement while completing my program.

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LIST OF SYMBOLS

A_h	Absolute humidity, lb. water/lb dry air (kg water/kg dry air).
MC	Moisture content, % dry basis.
MC_{in}	Moisture content, inlet, % dry basis.
MC_{out}	Moisture content, outlet, % dry basis.
R_{d_a}	Rate of wet air movement, cfm/min (m^3/min).
R_{wa}	Rate of dry movement, cfm/min (m^3/min).
S_{ha}	Specific heat of air, .24 BTU/lb air/°F (10004 J/kg air/°C).
T	Temperature °F (°C).

LIST OF TERMS

Air Lock	A device which inhibits air passage while allowing for grain movement.
Concurrent Flow	Condition which exists when grain and air move in the same direction.
Concurrent Section	That portion of the dryer which includes the heating section, tempering section, and related components so as to allow for concurrent flow of product and air.
Cooling Air	Ambient air which is forced through the cooling section.
Cooling Zone	That portion of the counter-flow section in which the cooling air and product have flow velocities in opposite directions.
Counter-current Flow	Condition which exists when grain and air move in opposite directions.
Counter-flow Section	That portions of the dryer which includes the cooling section and related components to allow for counter-flow of air and product.
Cross Flow	Condition which exists when grain and air flow in perpendicular directions.
Heating Air	Air that has passed through the burner and which is forced through the heating section
Heating Zone	That portion of the concurrent section in which the heating air and product have flow velocities in the same directions.
Product	The biological material being artificially dryed.

Spreading Device	A device which mechanically introduces a layer of wet grain on top of the heating section.
Tempering Zone	That portion of the concurrent section in which heated grain travels in an environment free of air movement allowing the grain to temper.

INTRODUCTION

The first section of this study involves the design, construction, and testing of a pilot-scale dryer using corn as the product. The pilot-scale dryer uses the principle of concurrent heating and counter-flow cooling.

The maximum product temperature is lower than the maximum heating air temperature (see Fig. 1). In a cross-flow grain dryer, the temperature of the product will approach or equal the maximum value of the heating air (see Fig. 2). Corn was used as the testing medium.

Background on Concurrent Flow Dryers

A concurrent flow grain dryer, patented in the United States by a Swedish inventor (Öholm, 1955), features a method of transferring energy to the grain in the upper drying bed without increasing the absolute humidity of the heating air (see Fig. 3). Hot liquid can be circulated through pipes to transfer heat to the grain. The concept could prove practical if direct fired burners could not be supplied with the relatively clean burning fuels now available.

A portable concurrent flow grain dryer is produced by the M and W Gear Company (see Fig. 4). The M and W

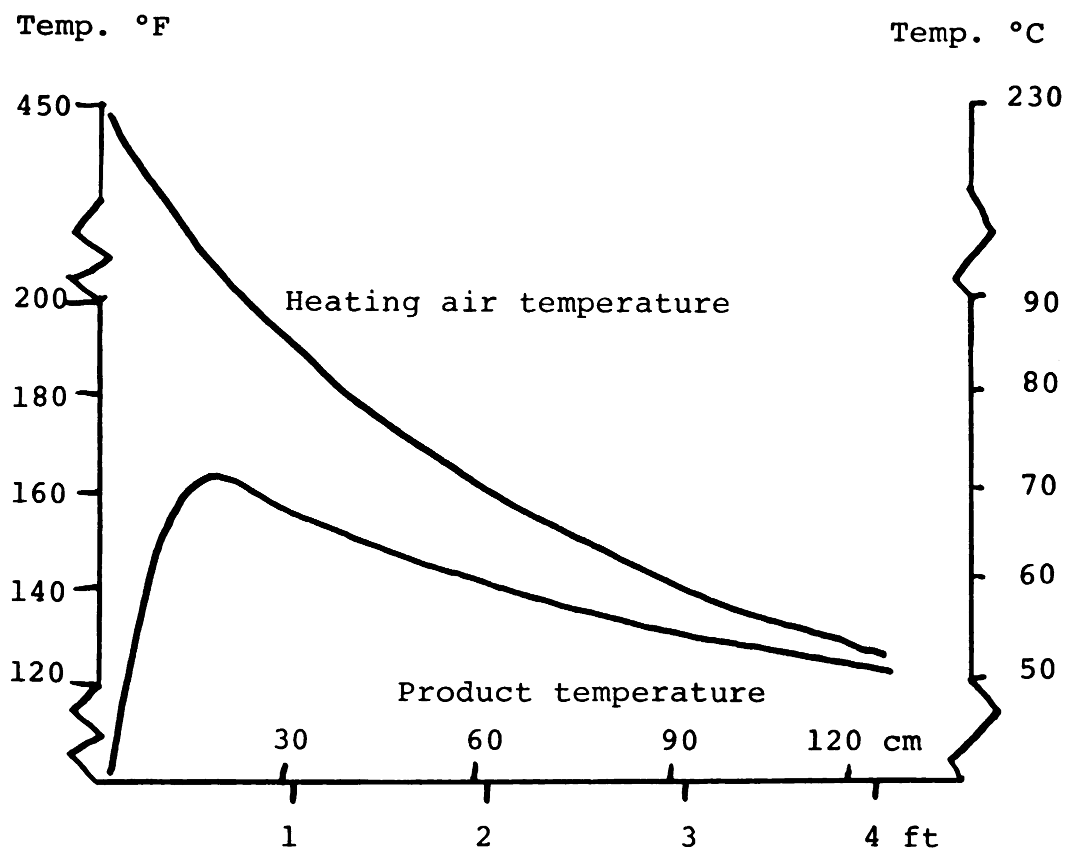


Figure 1.--Theoretical Concurrent Air and Grain Temperatures.

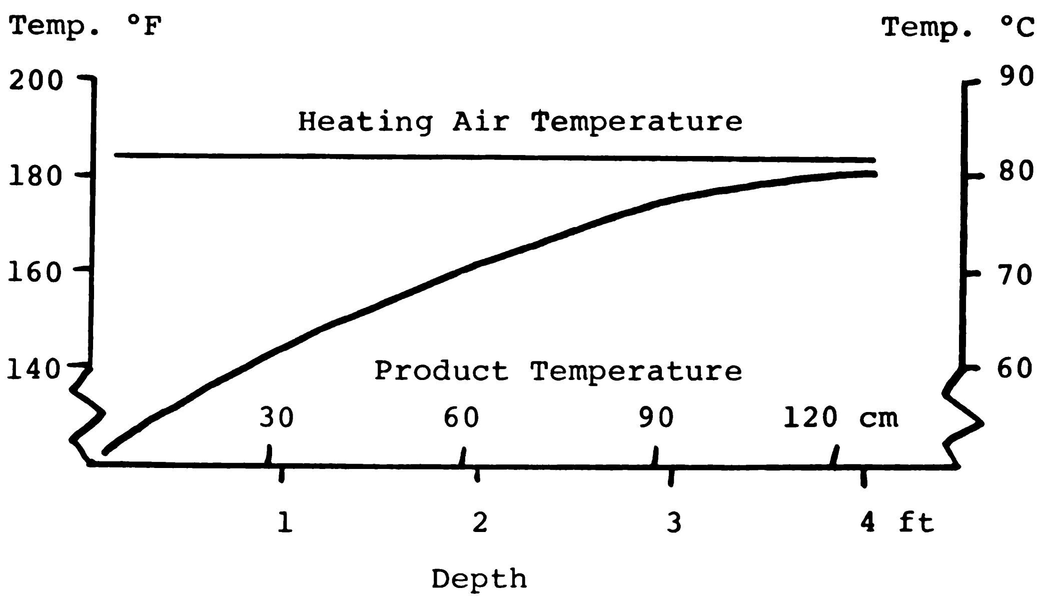


Figure 2.--Theoretical Crossflow Air and Grain Temperature

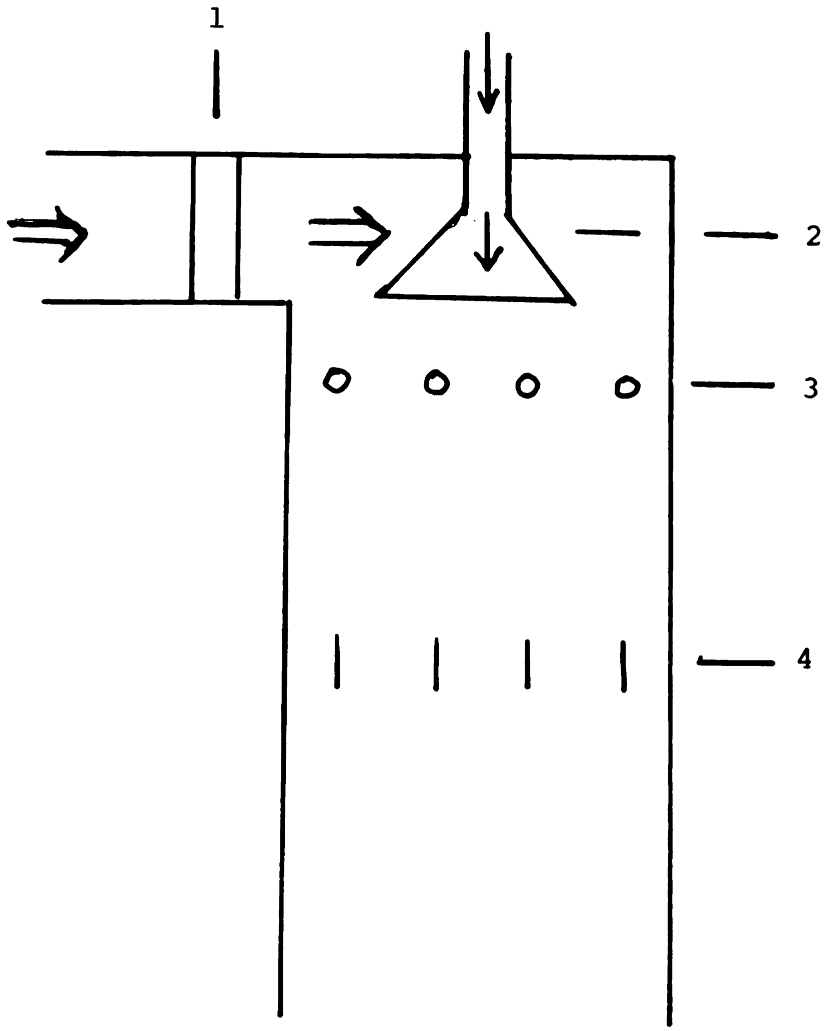


FIGURE 3.--Öholm Grain Dryer.

Legend:
1. Heating element
2. Grain inlet
3. Heating pipes
4. Heating air exhausts

↓ Grain velocity

⇓ Hot air velocity

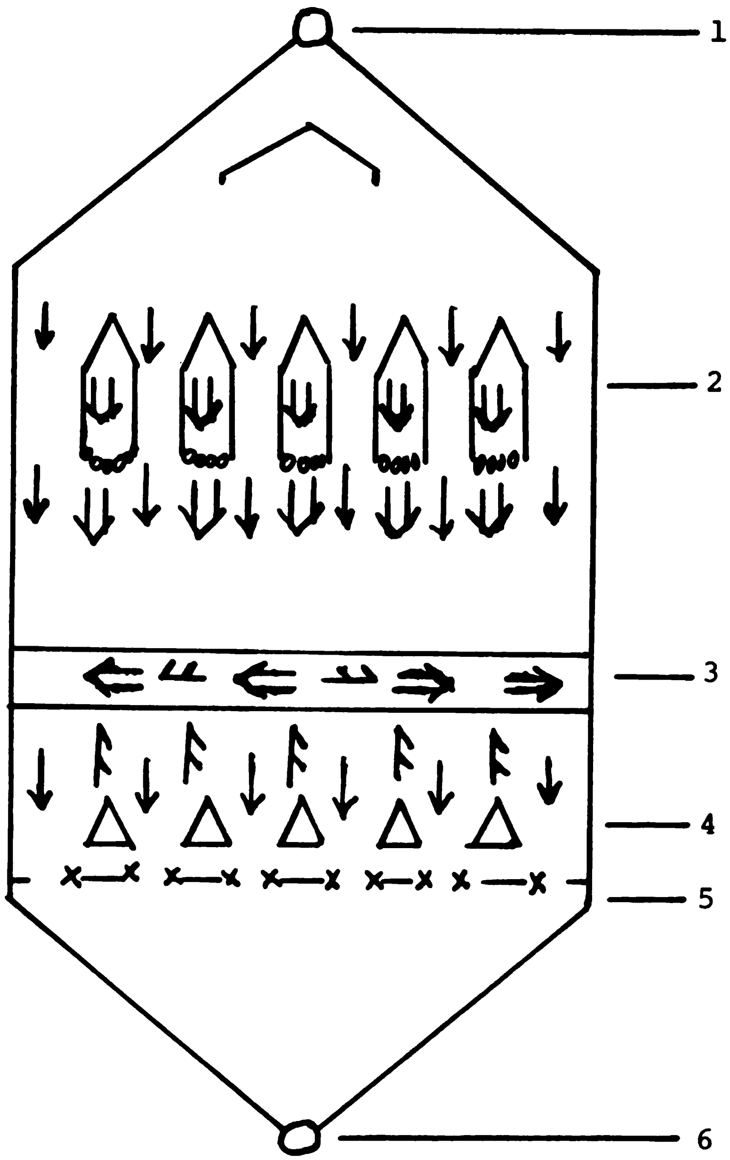


FIGURE 4.--M and W Perfect Kern'l Grain Dryer

Legend:
1. Grain inlet auger
2. Hot air inlet
3. Hot air and cooling air exhaust
4. Cooling air inlet
5. Grain metering mechanism
6. Grain outlet auger

↓ Grain velocity
⇓ Hot air velocity
↾ Cooling air velocity

Perfect Kern'l grain dryer is similar in design and principle to a drying apparatus patented by Graham (1967a). The dryer is similar in design to the first concurrent flow dryer constructed by Anderson (1972). The heated air temperature is limited to 300°F (149°C) with a grain throughput rate of approximately 2.5 bushels of corn per hour per square foot (.85 m^3/m^2) (Graham 1967).

Mühlbauer et al., (1971) constructed a concurrent flow dryer in which the heating air escapes upward through the grain placed on top of the dryer (see Fig. 5). No detrimental effect on grain quality or dryer efficiency was observed.

One of the first commercial continuous flow grain dryers using a concurrent heating section and a counter-flow cooling section is described by Anderson (1972). The dryer has no spreading device (see Fig. 6) and is reported to cause excessive grain damage as a result of overdrying the grain. Bees wings collected in the valleys and was believed to have been responsible for many fires. The grain flow rate was reported to be approximately five bushels per hour per square foot (.18 m^3/m^2). The temperature of the heating air was limited to 350°F (177°C) in order to reduce the fire hazard and preserve grain quality. Another problem encountered was that of unequal heating air temperature distribution across the top of

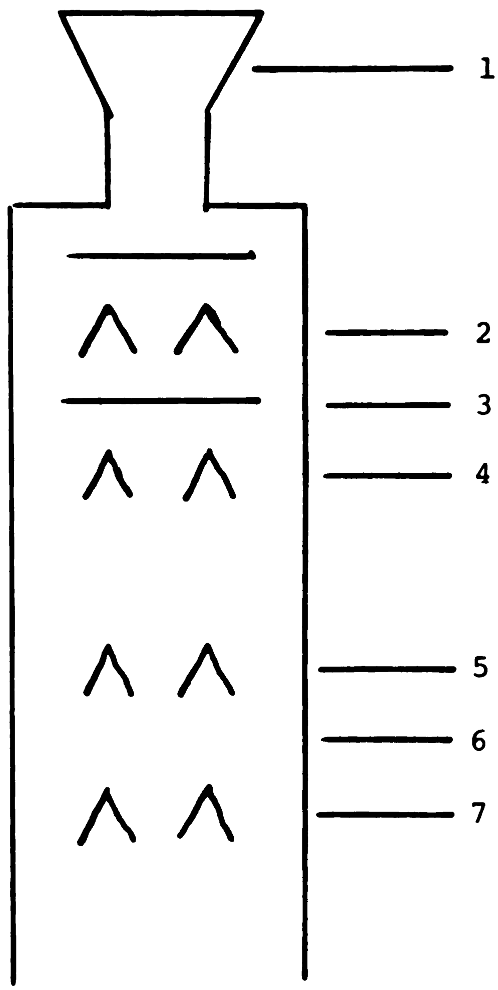


Figure 5.--Mühlbauer Grain Dryer.

Legend:
1. Grain inlet
2. Heating air inlet
3. Heating section
4. Heating air exhaust
5. Cooling air exhaust
6. Cooling section
7. Cooling air inlet

the heating bed due to heat losses through the long air ducts.

A second prototype was constructed by Anderson (1972) with a spreader built on top of the heating section. The spreading device (see Fig. 7) eliminated many of the problems encountered with the first prototype. A point of interest is that the suggested safe operating temperature is 525°F (274°C) for corn, and is limited by the ignition point of bees wings which was experimentally found to be between 550 and 575°F (287 and 302°C).

Spreaderless, continuous flow concurrent drying and counter-flow cooling grain dryers are being constructed for commercial grain operations by Westelaken (1975). The dryers use a "grid" type floor with insulated round steel tubes located above the heating bed to introduce the heating air to the product (see Fig. 8). The steel "grid" floor combined with high air and product flow rates is used to prevent the problems of other spreaderless designs while eliminating the need for the extra moving parts found in spreader-type dryers. Many of these dryers are multi-stage designs (see Fig. 9). Two or more concurrent heating stages are installed. Grain is allowed to temper between the heating stages. Improved grain quality and greater overall drying efficiency as a result of the extra heating and tempering sections are two benefits of using multi-stage dryers.

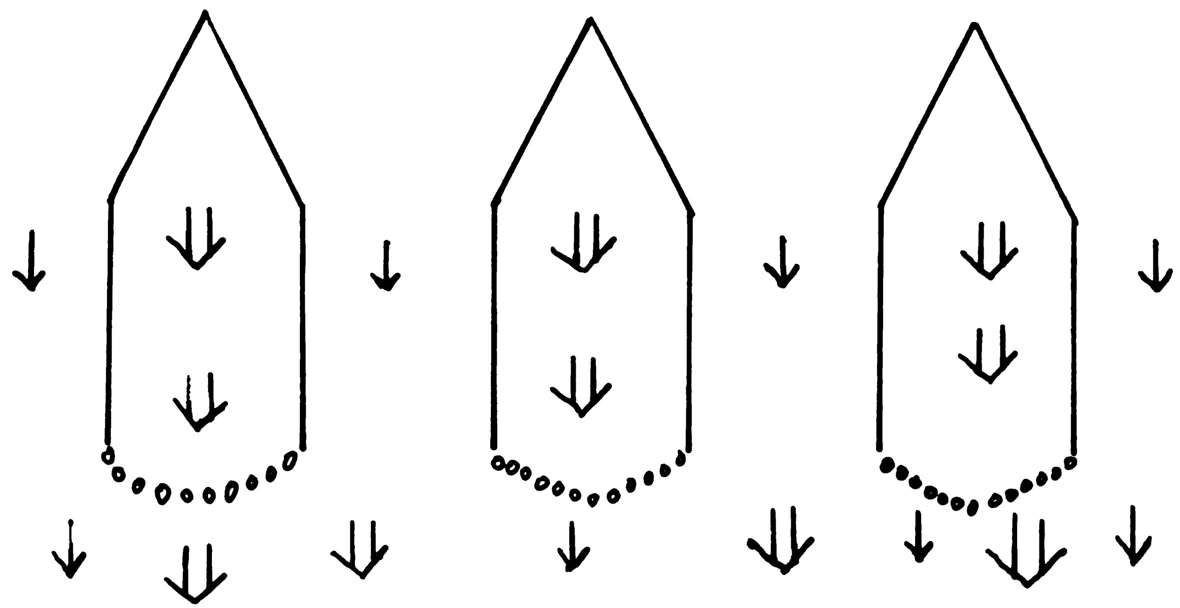


Figure 6.--Anderson Spreaderless Design.

Legend:
1. Hot air garner
↓ Grain velocity
⇓ Hot air velocity
ooo Hot air and grain boundary

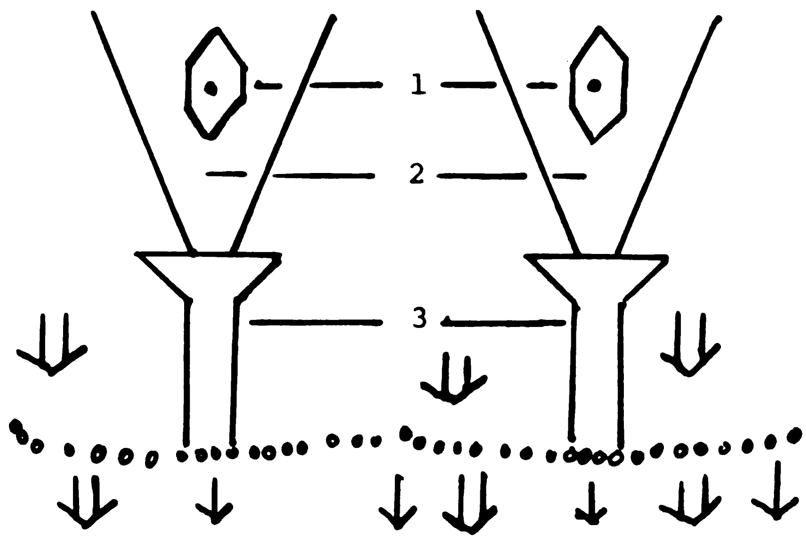


Figure 7.--Anderson Pendulum Spreading Device.

1. Pivot point for pendulum spreading device
2. Inlet grain hopper
3. Pendulum spreading device

⇓ Hot air velocity
↓ Grain velocity
ooo Hot air and grain boundary

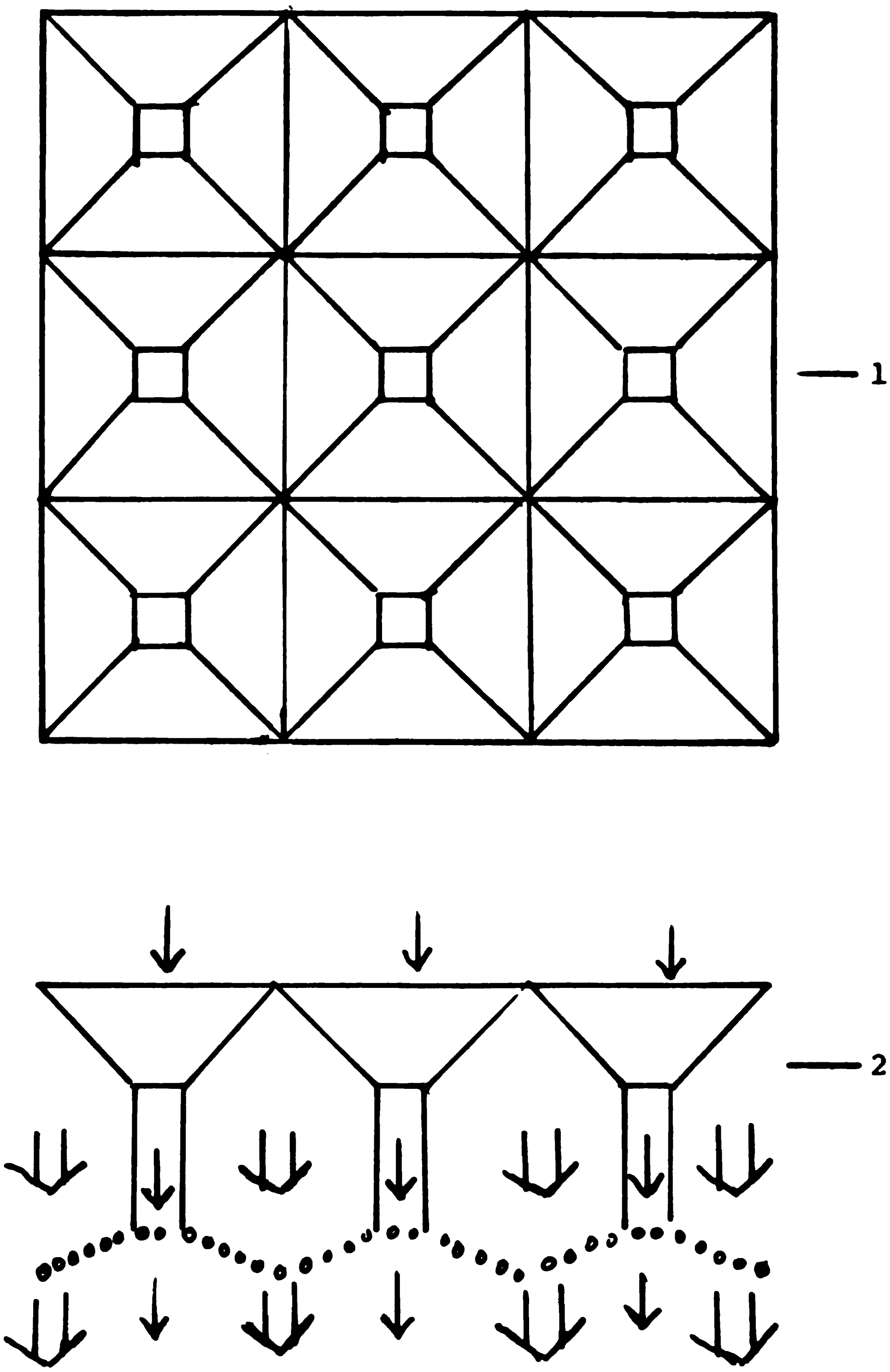


Figure 8.--Westelaken Floor.

Legend:
1. Top view of Westelaken floor
2. Side view of Westelaken floor

⇓ Hot air velocity

↓ Grain velocity

ooo Boundary between hot air and grain

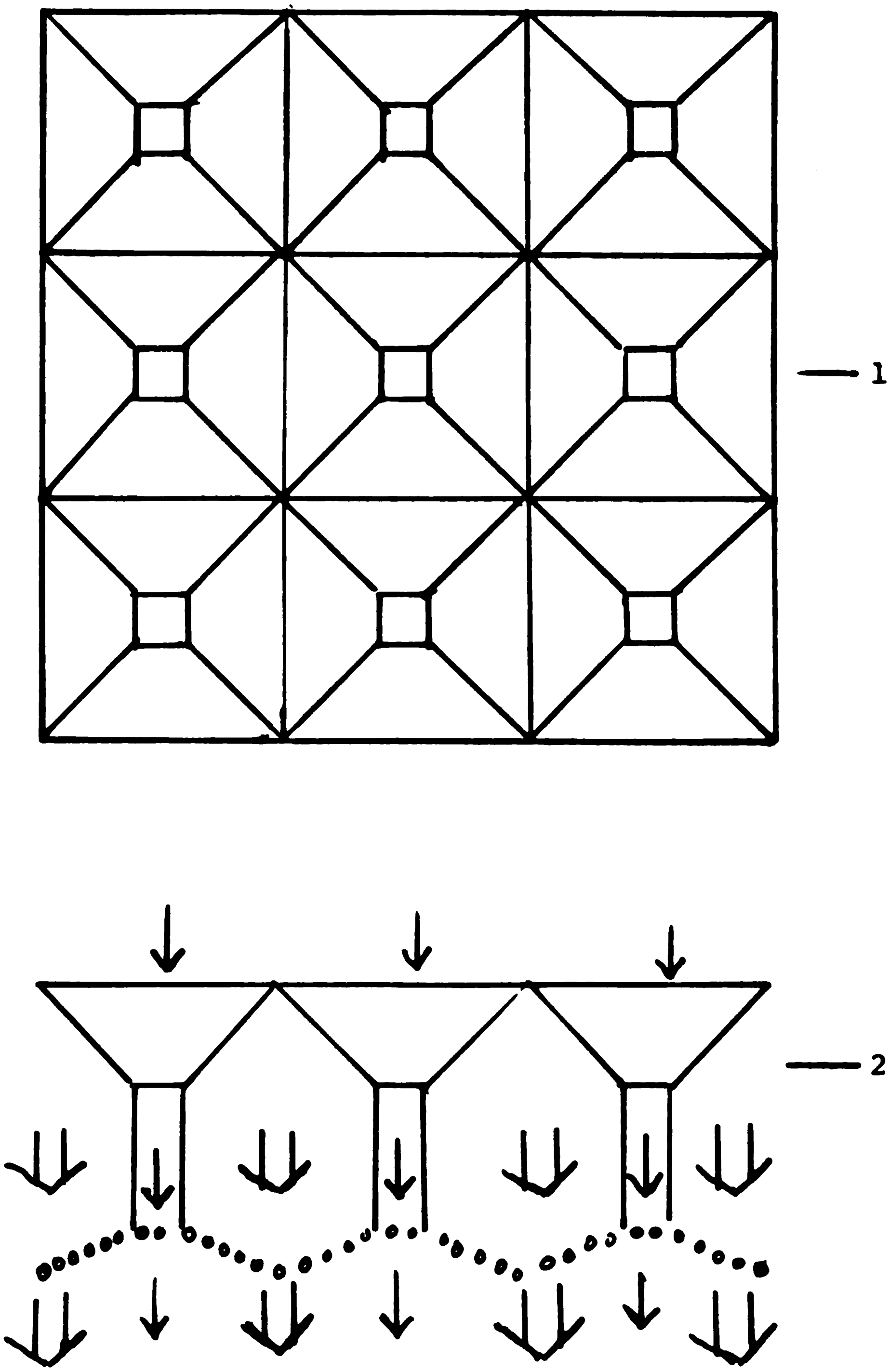


Figure 8.--Westelaken Floor.

Legend: 1. Top view of Westelaken floor
2. Side view of Westelaken floor
⇓ Hot air velocity
↓ Grain velocity
ooo Boundary between hot air and grain

A modification of the multi-stage concurrent flow dryer (see Fig. 10) is the addition of heating air exhaust recirculators (Bakker-Arkema, 1977). Exhaust air from the first drying zone is heated and circulated through the second heating zone. The exhaust air from the second heating section is circulated through the third heating stage. This modification will reduce the amount of energy which must be used to heat the incoming air for the second and third drying zones.

Background on Concurrent Flow Laboratory Dryers

Carrano (1970) designed, constructed, and tested the first Michigan State University prototype of the concurrent flow laboratory dryer. The dryer was made of square steel sections bolted together and insulated. Corn was the product dried. Spreader and spreaderless versions of the dryer were tested. An air lock was used to prevent the downward flow of air in the counter-flow cooling section. No means of replenishing the wet grain supply was provided. Testing was limited by the amount of grain which could be loaded into a sealed holding hopper on top of the dryer. A 47% reduction in germination was reported for grain dried at 450°F (232°C) at a flow rate of approximately 3.2 bushels per square foot per hour (.13 m_3/m_2/hr).

The Carrano square sectioned dryer was replaced by a round sectioned dryer (see Fig. 11) by Gygax (1972).

Figure 9.--Westelaken Three Stage Dryer.

Figure 10.--Westelaken Three Stage Dryer with Heating Air Recirculators

Legend:
1. Grain bin
2. First hot air inlet
3. First drying zone
4. First hot air exhaust
5. First tempering zone
6. Second hot air inlet
7. Second drying zone
8. Second hot air exhaust
9. Second tempering zone
10. Third hot air inlet
11. Third drying zone
12. Third hot air exhaust and cooling exhaust
13. Cooling zone
14. Cooling air inlet
15. Metering rolls
16. Dry grain discharge
17. First stage heating air exhaust recirculator
18. Second stage heating air fan
19. Second stage heating air exhaust recirculator
20. Third stage heating air fan

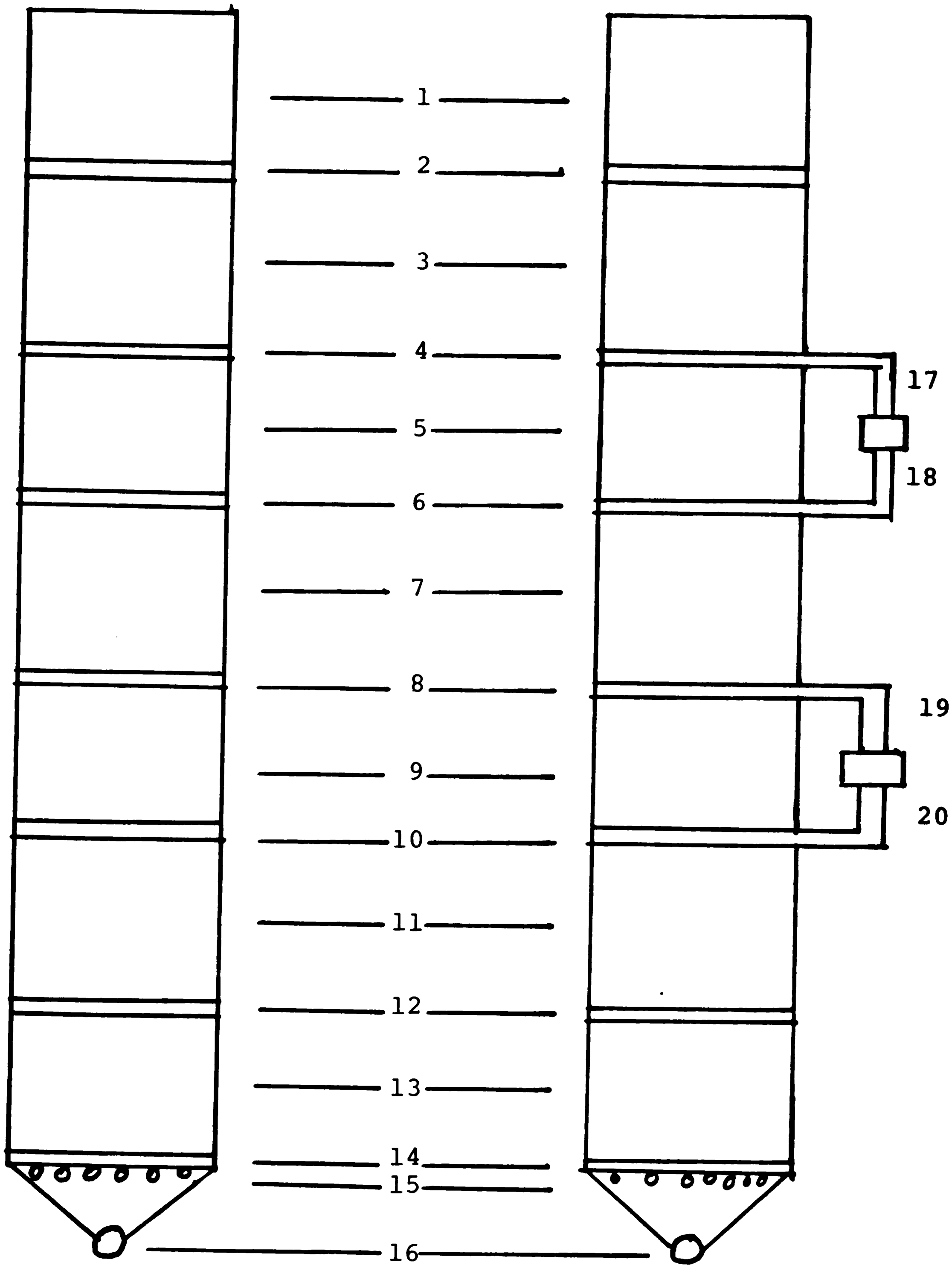


Fig. 9

Fig. 10

Figure 11.--Pilot-Scale Dryer Before Modifications.

Legend:
1. Bucket elevator
2. Mechanical air lock
3. Grain storage hopper
4. Mechanical grain spreading device
5. Heat air enters here
6. Concurrent drying section
7. Perforated circular drying section metering and unloading mechanism
8. Screen funnel-heated air exists here
9. Mechanical air lock
10. Cooling fan
11. Cooling air exits here
12. Counter-current cooling section
13. Perforated circular cooling section unloading mechanism
14. Discharge auger
15. Heated air fan
16. Burner

↓ Grain velocity
⇓ Heating airflow velocity
ooo Cooling airflow velocity

A spreading device (see Fig. 12) was constructed and put on top of the heating bed. Heavy motors and gear boxes powered the rotating spreader and rotary air lock. The dryer had many air leaks and an unreliable grain through-put metering mechanism.

The dryer used in this study had no speader or rotary air locks and had fewer moving parts. The pilot-scale dryer has a high degree of reliability when compared to previous laboratory dryers. The rotary air lock used in the Gygax dryer was eliminated in the pilot-scale dryer used in this study by an air restriction tube (see Fig. 13). The circular feed mechanism was replaced by a grain collection cone and metering auger.

Objectives

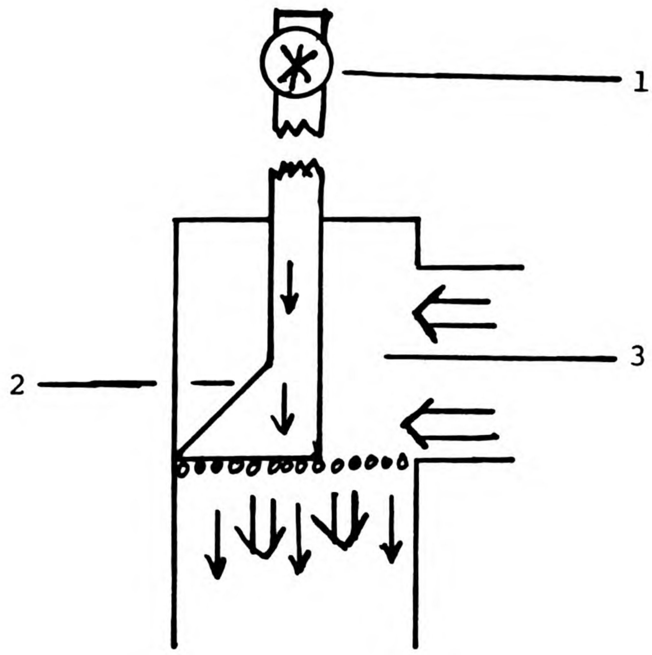
1. To modify and test a concurrent flow laboratory grain dryer.
2. To conduct drying tests with corn and soybeans.
3. To gain experience and knowledge in the field of continuous flow concurrent drying of grain.

Figure 12. Revolving Spreading Device.

Legend:
1. Rotary air
2. Rotary spreader
3. Hot air inlet
- ⇓ Hot air velocity
- ↓ Grain velocity
- ooo Boundary between hot air and grain

Figure 13.--Modified Spreaderless Design.

Legend:
1. Air flow restriction tube
2. Grain distribution tube
3. Hot air inlet
- ⇓ Hot air velocity
- ↓ Grain velocity
- ooo Boundary between hot air and grain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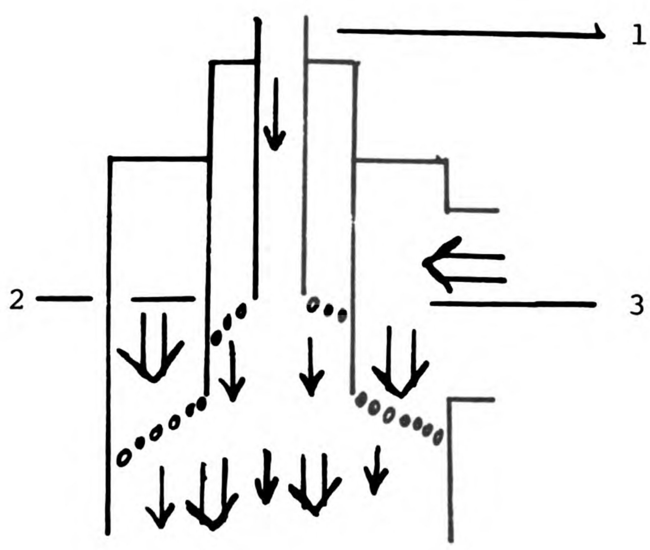
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DESCRIPTION CONSTRUCTION AND TESTING OF DRYING APPARATUS

The pilot-scale laboratory dryer is an evolutionary machine. Many of the parts on the dryer to be described have been used on previous prototypes. Since the laboratory dryer is small when compared to larger commercially available dryers, care must be taken not to assume that problems common to each can be solved for both by using similar solutions. Airflow and heating air temperature distributions may not be a problem in a small laboratory dryer and may be a relevant problem in a larger scale machine.

The grain and airflow paths through the present machine are illustrated in Figure 14. The Figure illustrates components to be discussed.

Concurrent Section

The concurrent section is that part of the dryer in which the heating air is introduced and forced through the moving grain bed. The concurrent section of the dryer also includes the grain flow metering mechanism. Figure 15 illustrates the components of the concurrent section.

Figure 14.--Overall View of Pilot-Scale Concurrent Flow Grain Dryer.

Legend:
1. Bucket elevator
2. Grain storage hopper
3. Natural grain airlock
4. Heating air and grain boundary area
5. Concurrent drying section
6. Heating air exit
7. Tempering section
8. Grain flow rate metering auger
9. D. C. shunt wound variable speed motor
10. Cooling air exit
11. Cooling section
12. Cooling air entrance
13. Cooling section air lock
14. Cooling section discharge auger
15. Cooling air fan
16. Heated air fan
17. Burner

↓ Grain flow

⇓ Hot air flow

F Cooling air flow

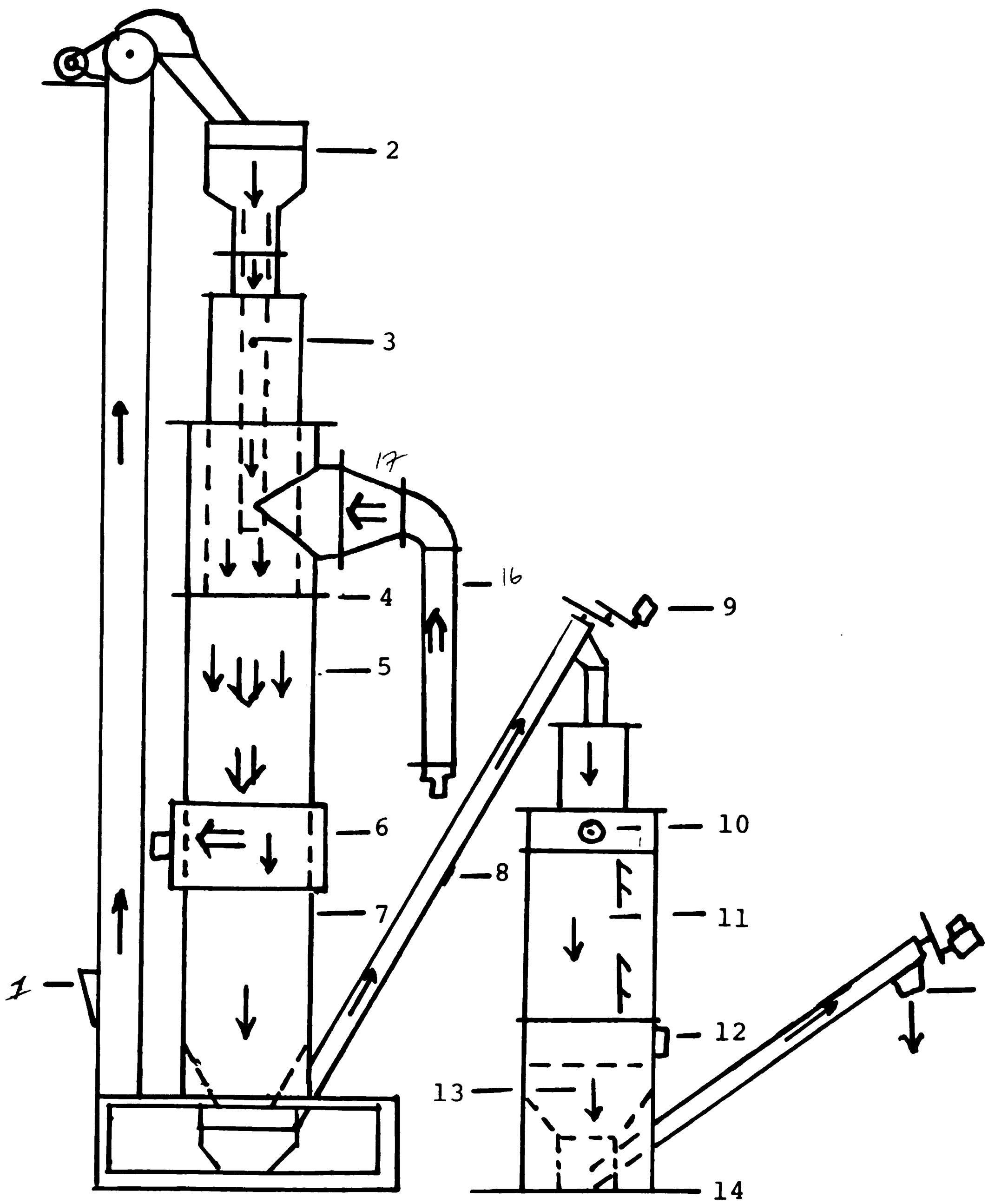
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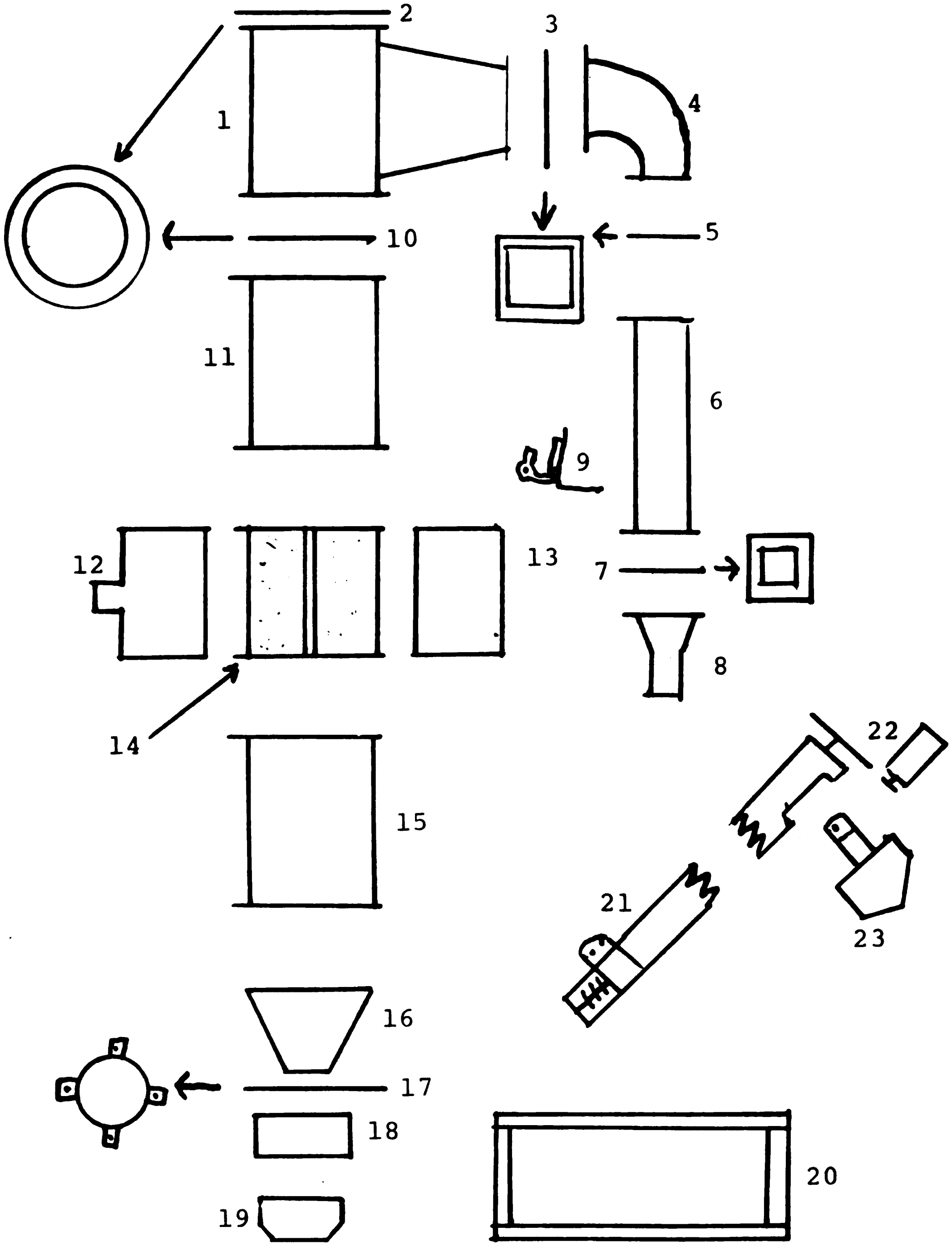
Figure 15. Exposed View of Concurrent Section.

Legend:
1. Heated air introduction chamber
2. Asbestos gasket
3. Asbestos gasket
4. Heated air elbow
5. Asbestos gasket
6. Burner
7. Gasket
8. Transition piece
9. Burner ignition and safety controls
10. Asbestos gasket
11. Concurrent heating section
12. Air shroud with exit
13. Air shroud
14. Heated air exit
15. Tempering zone
16. Grain collection cone
17. Grain collection cone supporting
18. Grain collection hopper shield
19. Grain collection hopper
20. Concurrent section base support frame
21. Concurrent grain metering discharge auger
22. Variable speed D.C. shunt wound electric motor and speed reduction
23. Grain spout
24. Inlet fan and motor assembly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The tee section (1) is from a previous design of the dryer. Heating air is directed to the heating section from the burner via the tee section and elbow (4) which connects to the burner (6) and burner safety controls (9).

The burner and burner safety controls are from a previous dryer. A liquid petroleum tank (located outside of the building) provides the fuel for the burner. Safety devices include an automatic shut-off valve to guard against burner malfunction. A transition piece (8) was constructed of galvanized sheet metal to connect the burner to an inlet air supply hose. All air hoses used on the dryer are four inches (10.16 cm) in diameter and are made of wire-reinforced vinyl. Inlet air is supplied by a 22 inch (56 cm) diameter forward inclined fan powered by a five horsepower motor (24).

Asbestos gaskets (10, 2, 3, 5, and 7) are used to prevent air leakage; 3/8 inch (9.5 in m) bolts of various lengths are used throughout the construction of the dryer.

The heating section (11) is three feet (91.44 cm) long with a one square foot (930 cm^2) cross-sectional area. The wet product and heating air meet and flow through this section in the same direction.

After the heated air travels the full length of the heating section, the air is exhausted through the heated air exhaust (14). Perforated sheet metal was welded to the inside of this structural piece. Shrouds (12 and 13) are placed over this section to provide a means of monitoring exhaust air properties.

After the heating air is exhausted, the grain continues to move downward. The tempering zone (15) is provided as a means of allowing the grain to remain warm and to allow for moisture redistribution within the individual product particles. Better product quality and greater overall dryer efficiency are reported by Foster (1964) as a result of tempering.

Grain exist and metering mechanisms (16-23) are located below the tempering zone. Grain is funneled into a metering auger (21) and hopper (19) by a cone made of galvanized sheet metal (16). The grain collection cone (16) is held into place by a ring with tabs welded to the side of the ring (17). The ring bolts on to the base (20) and prevents the long column of grain from forcing the cone downward. The grain collection hopper (19) was formed using galvanized sheet metal. The design allows for easy removal and replacement of the metering auger (21-23). Hoper side extentions were later added to prevent spilling upon filling the dryer initially. The concurrent section support frame (20) prevents the round portion and heated air assemblies from falling over. Styrofoam panels (not shown) were added to prevent an excessive heat loss through the bottom of the concurrent section.

The 4 inch (10.16 cm) in diameter metering auger (21-23) is placed with the inlet portion in the grain collection hopper (19). The auger sets at a 60 degree angle to the floor. A grain shield (23) was constructed and fitted to the auger to prevent grain spilling from the auger discharge to the inlet of the counter-flow section of the dryer. The auger is covered with fiber-glass insulation to prevent heat loss from the product.

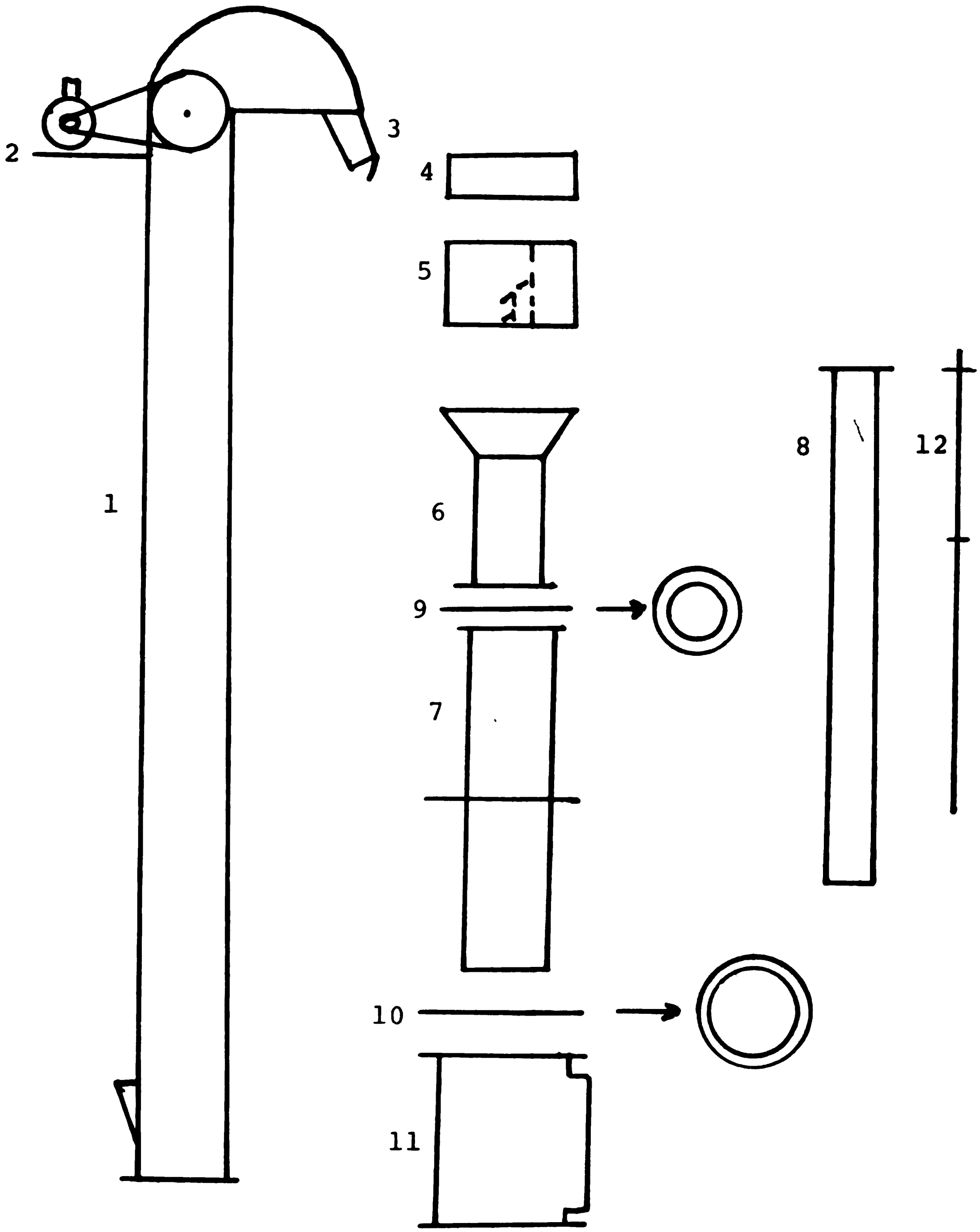
A variable speed D.C. shunt wound electric motor (22) and control are used to power the metering auger. A gear reduction shaft and extra pulleys are used to arrive at a proper range of discharge rates of the product being dried. The variable speed motor allows for infinite discharge auger speeds and constitutes an easy method for change of the grain throughput rate.

Grain Level Maintenance and Air Lock Components

The purpose of the grain level maintenance and air lock components is to maintain a supply of wet grain above the heating section of the dryer. A natural air lock is formed which prevents the upward escape of heating air. Figure 16 illustrates an exposed view of this section of the dryer.

Figure 16.--Exposed View of Grain Level Maintenance and Airlock Components.

Legend:
1. Bucket elevator
2. 1/3 horsepower capacitor-start electric motor
3. Spout and deflector plate
4. Hopper shield
5. Microswitch section
6. Lower hopper section
7. Grain distribution tube
8. Airflow restriction tube
9. Asbestos gasket
10. Asbestos gasket
11. Heated air introduction chamber
12. Inlet grain temperature thermocoupe support



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A bucket elevator (1) is used to transport the product from the floor to the wet grain holding hopper (4-6). Micro switches (5) are positioned to assure that the wet grain holding hopper would have an adequate amount of grain during the tests. The micro switches engage a relay (not shown) which in turn power a 1/3 horsepower capacitor-start motor (2).

The grain distribution tube (7) spreads grain over the heating bed and is the means by which the heating air is introduced to the wet product above the drying zone (see Fig. 13). The grain distribution tube (7) is nine inches (23.9 cm) in diameter and four feet (12 cm) long. Two feet (60.5 cm) extend into the tee section (11) of the concurrent section. A donut shaped flange is welded to the middle of the grain distribution tube to support the tube above the drying bed. Heated air circulates around the two foot (60.5 cm) length of the grain distribution tube which fits inside of the tee section to prevent grain damage. An asbestos gasket is bolted between the tee section (1) and the grain distribution tube. The lower hopper assembly is bolted to a base welded onto the top of the grain distribution tube. A gasket is installed between the lower hopper assembly and the grain distribution tube.

The air restriction tube (8) is bolted to the lower grain hopper (6). This component is a 4 inch

(10.16 cm) diameter insulated aluminum tube 54 inches (1.37 m) in length. Wet product fills the tube when the dryer is in operation and prevents any significant leakage of heating air. The discharge end of the air restriction tube empties wet grain into the grain distribution tube (7).

Inlet grain temperature thermocouples allow determination of the inlet grain temperature, thereby indicating if there is any significant air leakage. The support is constructed of a steel rod to allow placement of the thermocouples at 12 inches (30.5 cm) and 36 inches (91.5 cm) below the hopper section.

Counter-Flow Section

The product leaves the metering auger of the concurrent section (see Fig. 17). The purpose of the counter-flow section is to cool the grain thoroughly in a counter-flow fashion. The driest and coolest grain is exposed to the coolest air, thereby minimizing quality deteriation. The cooling section of the dryer is constructed of round sections one square foot (929 cm^2) in area bolted together.

The product level is maintained by two micro switches (3A) located in the upper region of the cooler (3). The microswitches are similar in design and operation to the micro switches installed in the grain level maintenance portion of the concurrent section. Two shields (1 and 2) are constructed of tin and provide access to the micro switches. The micro switches engage and disengage the discharge auger (13). The auger does not operate continuously; therefore, the counter-flow section of the dryer is in reality not a continuous flow mechanism.

Exhaust air is collected and exited through a four inch (10.16 cm) diameter pipe (3b) so that the dry bulb and wet bulb temperatures can be measured.

The cooling air exhaust and counter-flow product level maintenance chamber (3) is constructed of 20 gauge sheet metal. This section supports the metering auger and is bolted to the middle counter-flow section via a gasket (4).

The cooling of the grain takes place in the middle counter-flow section (5). This two foot (60.96 cm) long section of the dryer was used on previous dryers and needed no modifications for use on this model. Room temperature cooling air is introduced to the product in the lower counter-flow section (7) through a perforated wedge (7a) formed of perforated sheet metal. The wedge is bolted to the inside of the round section. A square hole exists in the side of the round section to allow cooling air to travel upward through the cooling bed. A transition (7b) allows a four inch (10.16 cm) diameter hose to be installed between the cooling bed and cooling fan (16).

The bottom of the counter-flow section is made air-tight by a tin plate (1) and a gasket (10) bolted to the bottom between the base (12) and lower counter-flow section (7). The base (12) is constructed of one inch (2.54 cm) welded square tubing.

Cooling air is provided by a 15 inch (38.1 cm) centrifugal fan (16) that is powered by a two horsepower three phase motor. A laminar flow element (not shown) is placed between the fan and transition. Two pieces of hose connect the three components. Cooling airflow may be changed by adding shutters or changing fan and motor pulley sizes.

The product discharge mechanism is very similar in action to the unloading mechanism found in the concurrent section. A grain collection funnel (18) is held in place by sheet metal screws. The product is funneled into a collection basin (9) where the discharge auger's (13) inlet is placed. The auger is placed inside of the lower counter-flow section (7) near the bottom and sealed in place to prevent air leakage. A stand (not shown) is provided to support the discharge end of the auger.

A temporary spout and flow diverter (not shown) were added near the inlet of the counter-flow section so that the counter-flow section of the dryer could be by-passed.

Figure 17.--Exposed View of Counter-Flow Section.

Legend:
1. Micro switch inspection plate
2. Microswitch inspection plate
3. Cooling air exhaust and counter-flow product level maintenance
3a. Micro switches
3b. Exhaust air exit
4. Gasket
5. Middle counter-flow section
6. Gasket
7. Lower counter-flow section
7a. Perforated air introduction wedge
7b. Fan to counter-flow section air transition
8. Product collecting funnel
9. Product collection basis
10. Gasket
11. Counter-flow section end plate
12. Counter-flow section base frame
13. Discharge auger
14. Cooling fan

Instrumentation

The instrumentation of a pilot-scale laboratory dryer distinguishes a pilot-scale dryer from larger dryers. A description of the instrumentation is summarized in Table 1.

The accurate measurement of product moisture content is of primary importance to those dealing with biological products. Efficiency of the pilot scale dryer is calculated using the change in grain moisture content and amount of energy used to change the moisture content. A Steinlite moisture meter measures dielectric properties of the product being tested to indirectly determine moisture content.

An oven dry method (Brooker et al., 1974) was used to directly measure the moisture content of both corn and soybeans. Results are compared to those obtained using the Steinlite. The results indicated that the Steinlite was accurate when compared to the oven dry method.

Air flow of heating and cooling air is accomplished by the use of a laminar flow element and a calibrated manometer installed in the heating bed at 6, 12, and 24 inches (15.24, 30.48, and 60.97 cm) so that pressure drop across the drying bed could be measured. The same plastic hoses that connect the laminar flow element to the manometer were used to correct the pressure taps to the manometer.

Humidity determination is accomplished by two methods. Relative humidity of ambient room air is determined using the Bendix Aviation psychometer (see Table 1). Wet bulb thermocouples are installed at the air outlet of the heating air fan (8 and 9) air outlet of the concurrent section (10 and 11) and air outlet of the counter-flow section (12 and 13). The wicks are changed and inspected before each run.

Air and grain temperatures are closely monitored. Heated air temperatures are measured separately by a two channel Texas Instrument recorder and asbestos-insulated iron-constantan thermocouple wires (6 and 7). A 24 channel Texas Instrument recorder is used to monitor the copper-constantan thermocouples.

The inlet grain temperature is measured by inserting a mercury in glass thermometer in the inlet grain before being loaded into the dryer. A second method involves installing thermocouples (1 and 2) in the air restriction tube as described in the section titled, Grain Level Maintenance and Air Lock Components.

Air leakage should cause the bottom thermocouple to record a significantly higher temperature than the top thermocouple. Heating air was not lost through the open top of the dryer as the thermocouples in the air

TABLE 1.--Summary of Monitoring Equipment.

Instruments	Description--Accuracy
1. Manometer	Meriam Model 40GD10WM-6. Accuracy ± 0.02 inch water
2. Laminar Flow Elements	Meriam Model 50 MC2-4p. Accuracy ± 0.05% of calibration curve
3. Recorder	Texas Instruments twenty-four Channel Model EMWT6B Accuracy ± 0.75°F, linearity ± 0.3°F.
4. Recorder	Texas Instruments two channel Model P 502 W6A Accuracy ± 2°F, linearity ± 0.3°F
5. Moisture Tester	Steinlite Model 400 G, Accuracy ± 0.5% moisture content wet basis
6. Drying Oven	Blue M. Electric Company Model OV510, Mercury in steel thermometer used, Accuracy ± 2.5°F.
7. Room Air Psychometer	Bendix Aviation Corporation Model 573, Accuracy ± 5% relative humidity.

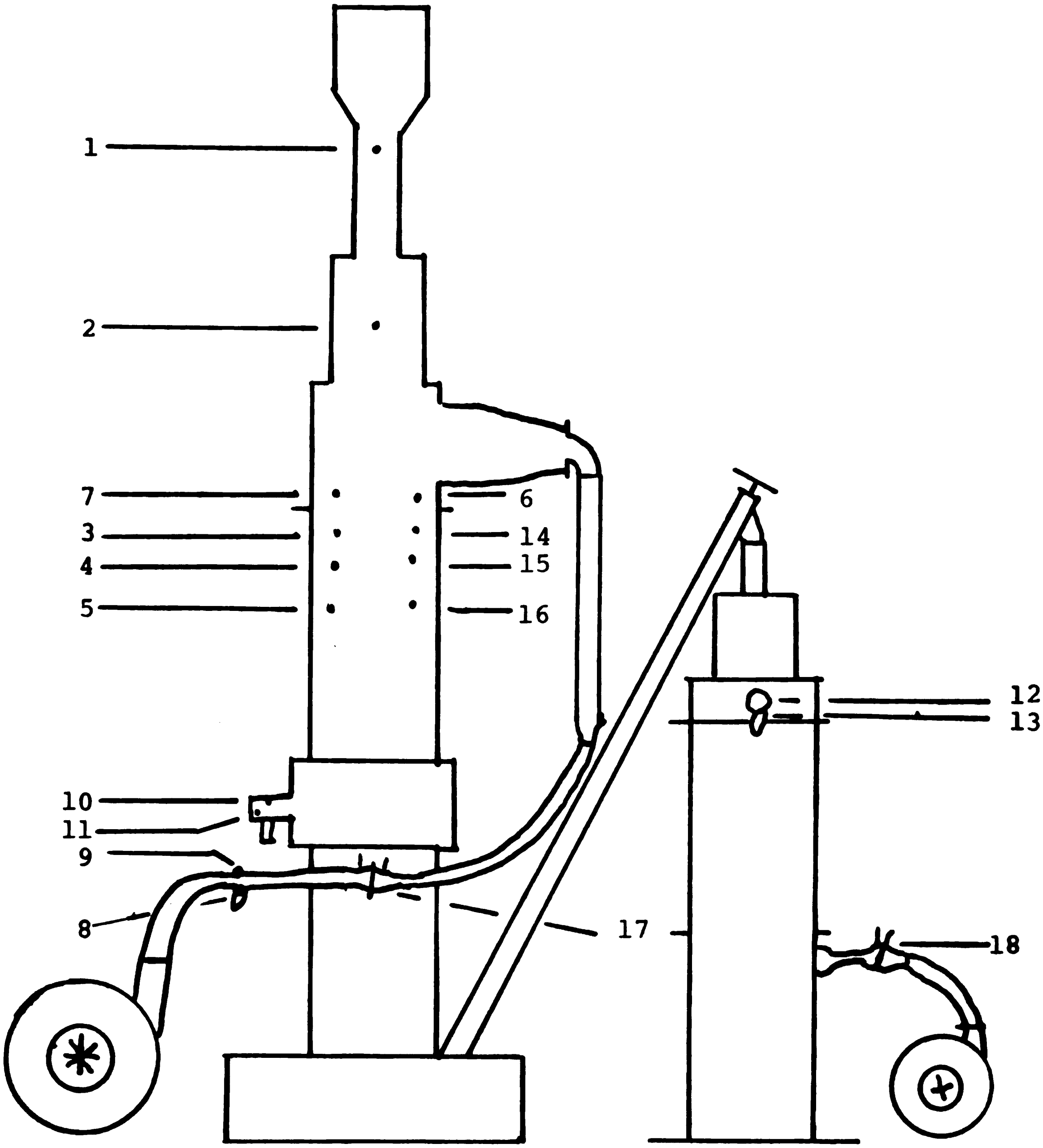
Figure 18.--Instrumentation Diagram.

Legend: Thermocouple Location

1. Inlet grain (12") (30.48 cm) above concurrent section
2. Inlet grain (36") (91.44 cm) above concurrent section
3. 6" (15.24 cm) concurrent section
4. 12" (30.48 cm) concurrent section
5. 24" (60.96 cm) concurrent section
6. Heated air immediately before introduction to concurrent section
7. Heated air immediately before introduction to concurrent section
8. Wet bulb inlet air
9. Dry bulb inlet air
10. Wet bulb concurrent exhaust air
11. Dry bulb concurrent exhaust air
12. Wet bulb counter-flow exhaust air
13. Dry bulb counter-flow exhaust air

Air Pressure Measurement Locations

14. 6" (15.24 cm) concurrent section
15. 12" (30.48 cm) concurrent section
16. 24" (60.96 cm) concurrent section
17. Concurrent inlet air laminer flow element
18. Counterflow inlet air laminer flow element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restriction tube recorded nearly identical temperature measurements throughout the tests.

Grain bed air and grain temperatures are measured by copper-constantan thermocouples at the same locations as the static pressure taps. The thermocouples are placed inside hollow steel rods about 1.5 inches (3.81 cm) from the wall of the dryer.

The outlet grain temperature is measured using a mercury in glass thermometer at the discharge collection container of the counter-flow section.

The throughput rate of the product is determined using a Toledo platform scale and watch.

Operation

Operation of the dryer consisted of three steps: (1) pre-equilibrium procedures; (2) testing after reaching equilibrium and, (3) post run operations. The first step was that of filling the concurrent flow section with previously dried products. Product to be dried was added after the concurrent section was filled. The metering auger was engaged and set to the desired discharge rate. The heating air fan, burner, and burner safety controls were adjusted to maintain the desired heating air temperature. Iron-constantan thermocouples and a recorder were used to determine the air temperature of the heating air. The cooling fan was engaged as soon as the first product was discharged out of the counter-flow section. A 24 channel recorder was used to determine if equilibrium had been reached. Ambient air conditions and inlet grain temperatures were recorded at this time.

Wet product had to be added throughout the test at regular intervals in order to keep heating air from escaping through the natural air lock. Inlet heating air temperatures were monitored and adjusted if needed throughout the drying run.

After reaching equilibrium, the throughput rate of product was determined with the platform scale and a watch. Outlet and inlet grain samples were collected for further analysis. Drying bed, inlet air, outlet air, wetbulb and inlet grain temperatures were noted.

After all the wet product has been fed through the dryer, the testing stopped and post run operations were begun. Previously dried product was placed on top of the wet product in the drying section to preserve the natural air lock. After all the wet product has been dried, the gas fired burner and controls were turned off. The heating fan continued to run until the heating zone of the dryer had cooled. The cooling fan was allowed to run until all the product was out of the counter-flow section.

Testing of Dryer Using Corn

Corn was used for initial testing of the dryer for two main reasons. More readily available information can be obtained about drying corn than soybeans or any other cereal grain. Standardized tests can be run on corn samples obtained from a drying run and compared to previous work. The tests include germination and Stein breakage tests (Anderson 1972).

The second reason for selecting corn as the best test medium is purely economical. The price of soybeans at the time of initial dryer testing was approximately three times the price of corn. Corn can also be rewetted and re-dried many times (Carrano 1970).

The first corn test will be described as it was the only experiment in which germination and Stein breakage tests were conducted. Later tests used rewetted corn from the first corn test.

Corn purchased for the test was ear corn and required shelling before being dried in the dryer. The steps followed in the operation of the dryer are described in the previous section (2.5). Three inlet corn samples were collected during the run. Inlet moisture content was measured before conducting the test using the Steinlite moisture meter to determine the approximate feed rate of the metering auger for obtaining a moisture content level of between 13 and 20 percent moisture content dry basis. Five outlet grain samples were collected during the test after the dryer had reached equilibrium. Data gathered during the test is found in Table 2.

Moisture content was checked on the three inlet grain samples and the five outlet samples the day after the test was conducted. The moisture content gradient within the dried kernals will be less the day after the testing than immediately after the run is completed.

Germination is a measure of the amount of damage done to a product during the drying process. Germination is a strict test of quality. A process which reduces the viability of the seed may or may not alter the usefulness of the product for its intended purpose.

One hundred sound kernals from each sample are placed inside special germination papers and soaked with water. After a week, the papers are unwrapped and the number of normally germinating kernals are counted as the percent germination.

A standardized breakage test was performed on the eight samples. The samples were conditioned before the breakage tests were conducted. The amount of breakage is influenced by the moisture content of the grain. The samples were placed in screen trays inside a conditioning box. The conditioning box contains a circulation fan and pans of saturated sodium chloride salt solution in order to maintain a constant relative humidity of approximately 75%. The temperature of the conditioning box was approximately 80°F (26°C). The purpose of the conditioning box is to allow the samples to arrive at a uniform moisture content level of approximately 14% MC dry basis (Brooker 1974).

After a week, the samples were removed from the conditioning box. One hundred grams of grain which had been cleaned over a 3/16 inch mesh screen were used for the breakage tests.

The Stein breakage tester contains an inpeller which revolves on the inside of a container loaded with the 100 gram sample for a timed period of two minutes. After the sample is treated in the breakage tester, the sample is screened over a 12/64 inch round sieve. The sample is again weighed. The difference between the initial grain sample weight and the sample weight after the treatment is the percent breakage.

Heat balance calculations (see Table 3) determine the efficiency of the pilot-scale grain dryer with regard to energy consumed per unit weight of water removed. The air flow was obtained by the use of a laminar flow element and a manometer. Thermocouples at the heating air inlet and outlet were used to obtain the air temperatures used in the heat balance evaluations. The grain throughput rate was obtained by using a Toledo platform scale and a watch. Density of the air was determined from a psychrometric chart after the room air temperature and relative humidity were measured. The amount of water that was removed from the grain was measured one day after the testing was completed by using a Steinlite moisture meter.

The mass balance calculations (see Table 4) of the first corn run had to be calculated after the heat balance calculations were completed. The wet bulb thermocouple located in the heating air exhaust port produced erroneous temperature readings. Normally, heat and mass calculations are done independently to serve as a check for an error in the calculations or in gathering the data.

The mass of the water removed by the cooler was calculated. The wet and dry bulb thermocouples measured constant temperatures throughout the first corn test. The cooling air flow rate was determined by using a laminar flow element and a manometer. Ambient room air was used for cooling the grain through the counter-flow section.

The mass of water removed by the heating air was not measured due to the faulty thermocouple. The mass of water removed from the grain in the dryer was calculated by subtracting the water removed from the grain by cooling air from the total amount of water removed from the grain.

The heating value of the fuel, the amount of energy required to warm the heating air, and the combustion constant of the fuel are values which are used to obtain the mass of water added to the heating air due to combustion of the fuel in the direct fired burner. The heating air mass includes the water gained by combustion of the fuel and the mass of water removed from the grain.

The water mass of the ambient air is added to the heating air mass and constitutes the total water mass of the heating air. The total water mass of the heating air is divided by the dry airflow rate to determine the absolute humidity of the exhaust heating air.

The throughput rate of the dryer for the first test was 7.4 bushels per hour (.25 cubic meter per hour). The temperature of the heating air was 360°F (182°C) at an airflow rate of 128 CFM (3.62 m^3/min). The grain was dried from 29.5% to 22.5% moisture content dry basis. The germination and Stein breakage test show very little damage was done to the corn. Higher air temperatures and slower grain throughput rates were used in later tests.

After the first run was completed, modifications to the pilot-scale dryer were made. A grain shield at the top of the wet grain holding hopper (Fig. 16) and a shield for the grain collection hopper (Fig. 16) were installed. The train of the product metering auger (see Fig. 17) was redesigned to provide for a lower throughput rate of the dryer. After further testing, two copper-constantan thermocouples were installed on the inside of the air restriction tube to determine heating air loss and the inlet grain temperature.

TABLE 2.--Data Collected During the First Corn Drying Test.

Parameters	Measurements
1. Inlet Grain MC, dry basis	29.5%
2. Outlet Grain MC, dry basis	22.5%
3. Heating Air Temperature	360°F (182°C)
4. Inlet Temperature of Grain	39°F (2.9°C)
5. Outlet Temperature of Grain	80°F (27°C)
6. Test Weight of Inlet Grain	52 lb/bu (660 kg/m^3)
7. Test Weight of Outlet Grain	52 lb/bu (669 kg/m^3)
8. Grain Throughput Rate	412 lb/hr (184 kg/hr) 7.4 bu/hr (.25 m^3/hr 9.2 ft/hr (2.8 m/hr)
9. Ambient Air Relative Humidity	39%
10. Ambient Air Temperature	68°F (20°C)
11. Heating Air Exhaust Temperature	137°F (58°C)
12. Cooling Air Exhaust Temperature	83°F (28°C)
13. Cooling Air Wet Bulb Temperature	81°F (26°C)
14. Drying Bed Temperatures	
A. 6 inch (15.2 cm) depth	182°F (83°C)
B. 12 inch (30.4 cm) depth	176°F (80°C)
C. 18 inch (15.6 cm) depth	173°F (78°C)
15. Density of Air 0.074 lb/ft^3	(1.2 kg/m^3)
16. Air flow rate of heating air measured at ambient air conditions	128 CFM (3.62 m^3/min) 53 CFM/bu (51m^3/ton)
17. Air flow rate of cooling air measured at ambient air conditions	20 CFM (.6 m^3/min) 8 CFM/bu (7.7 m^3/ton)
18. Germination Tests	
A. Inlet Grain	39.3%
B. Dryed Grain	31.2%
C. % Decrease in Germination	21.6%
19. Breakage Tests	
A. Inlet Grain	8%
B. Dryed Grain	12%
C. Percent increase	50%

TABLE 3.--Heat Balance Calculations.

Conditions	Results
1. R_{wa} for heating air:	568.0 lb/hr (257.3 kg/hr)
Airflow rate X 60 X air density	
2. Heat needed to warm heating air:	41,464 BTU/hr (4.37×10^7 J)
$T \times R_{wa} \times S_{ha}$	
3. MC Change:	7%
$MC_{in} - MC_{out}$	
4. Dry matter throughput rate:	385.4 lb/hr (174.6 kg/hr)
Grain throughput rate X (1 - MC change)	
5. Water removed from grain:	29.091 lb/hr (13.18 kg/hr)
Dry matter rate X MC change	
6. Energy requirement for water removed:	1650 BTU/lb water removed
Energy required/amount of water removed	(3.842×10^6 J/g water removed)

TABLE 4.--Mass Balance Calculations.

Conditions	Results
1. R_{wa} for cooling air:	88.2 lbs air/hr (39.9 kg air/hr)
Air flow rate 60 air density	
2. Increase in absolute humidity of cooling air:	0.024 lb water/lb dry air (0.24 kg water water/kg dry air)
A_h cooling exhausair-A_h ambient air	
3. Mass of water removed by cooler:	2.12 lb water/hr (0.96 kg water/hr)
R_{wa} X Increase in absolute humidity	
4. Mass of Water Removed by Heating air:	26.97 lb water/hr (12.22 kg water/hr)
Water removed from grain-water removed by cooler	
5. Mass of Fuel burned:	2.13 lb fuel/hr (0.97 lb fuel/hr)
Heat needed to warm heating air/heating value* (19,444 BTU/lb)	
6. Mass of water added to heating air due to combustion of fuel:	3.49 lb water/hr (1.58 kg water/hr)
Mass of fuel burned X combustion constant**	1.63 lb water/lb of fuel
7. Total mass of water added to heating air:	30.46 lb/hr (13.461 kg/hr)
Mass of water added to heating air due to combustion + mass of water removed by heating air from grain	
8. R_{da} of heating air:	564.6 lb/hr (255.5 kg/hr)
$R_{da}/1 + H_h$	
9. A_h of heating air exhaust:	0.06 lb water/lb dry air (0.06 kg water/kg dry air)
$(R_{wa} - R_{da}$ X total mass of water$)/R_{da}$	

*Hall (1957).

**Chilton and Perry (1973).

SUMMARY

Pilot scale continues flow grain dryers can be used to predict the performance of a larger machine for a given set of conditions. Modifications can be made on pilot scale dryers easier and with less expense incurred than if the same modifications are made on larger dryers. Corn and soybeans were dried in the tests. Other products, e.g., rice, should be dried in a pilot scale dryer before attempts are made to dry the products in a larger machine.

Germination and breakage tests were conducted on samples taken during the first corn run with a 4% increase in the amount of breakage and an 8.1% decrease in germination caused by drying the corn in the pilot scale dryer at 360°F (182°C).

CONCLUSIONS

1. By using the pilot-scale concurrent flow dryer, performance of large scale concurrent flow dryers can be predicted.

2. Grain throughput rates are as important as heated air temperatures and flow rates in determining whether spreader devices are needed to preserve grain quality.

3. Proper instrumentation is necessary to the successful operation of a pilot-scale dryer.

4. A pilot-scale dryer should be designed to permit modifications with relative ease.

SUGGESTIONS FOR FUTURE STUDY

Humidity determination was a problem using wet bulb thermocouples during the tests.

A gas flow meter should be installed on the liquid petroleum feed line to the burner. The use of this meter would provide a check when heat and mass balances are calculated.

Air flow measurement is an important aspect of grain dryer testing. The laminar flow elements should be recalibrated or other air flow measurement methods installed to insure that airflow is accurately measured.

The conversion of the laboratory dryer to a multi-stage heating section dryer should be investigated as a method to increase the amount of water removed for a given amount of energy consumed without a reduction of grain quality.

The counter-flow section of the dryer is separated from the concurrent section of the dryer. The operation of the dryer could be simplified further if the counter-flow section were fitted directly beneath the concurrent section. Lack of ceiling clearance necessitated the separation of the concurrent and counter-flow sections.

More information needs to be gathered about the tempering section of the dryer to determine the optimum length for different initial product conditions with regard to quality retention and or gains in drying efficiency.

A heat exchanger was installed on the dryer during some of the corn runs (Sokhansanj 1977). The results were encouraging. Further work should be done in the area of heat exchangers and exhaust air recirculation.

APPENDIX

DRYING OF SOYBEANS IN A PILOT-SCALE CONCURRENT FLOW DRYER

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LIST OF FIGURES

LIST OF ABBREVIATIONS AND COMPUTER VARIABLE NAMES

MC	Moisture content
TDB	Dry bulb temperature
WGT	Weight
CFM	Cubic feet per minute
BTU	British thermal unit
wb	Wet basis (moisture content)

The following appear in the concurrent dryer analysis program:

AHI	Abolute humidity of air into dryer after heating
AHIC	Absolute humidity into counterflow
AHIO	Absolute humidity into concurrent section
AHO	Abolute humidity of concurrent exhaust
AHOC	Absolute humidity of counterflow exhaust
AHR	Total pounds of water removed by air in both sections per hour (lb/hr)
AHRA	Pounds of water removed per hour by air in concurrent section (lb/hr)
AIRC	Countercurrent airflow (CFM)
AIRH	Concurrent airflow (CFM)
BDO	Test weight of dryer output (lb/bu)

BTU	Net energy into system (BTU/hr)
BTUPP	Energy consumed per pound of water removed (BTU/lb)
CAP	Grain flow rate out (bu/hr)
CFP	Ambient air density (CUBIC FEET/pound)
DM	Dry matter (lb)
GBTU	Gross energy into system (BTU/hr)
PH	Pounds of dry air per hour through concurrent section (lb/hr)
PHC	Airflow in cooler (lb/hr)
PM	Grain flow rate out (lb/min)
PRO	Propane burned (lb/hr)
TDBI	Ambient dry bulb temperature (°F)
TH	Heated air temperature (°F)
TGE	Change in energy of grain due to changes in temperature and moisture content in and out
TO	Grain temperature out (°F)
TI	Grain temperature in (°F)
TOT	Grain flow rate out (lb/hr)
WBU	Water removed from grain (lb/bu)
WCI	Wet basis moisture content of grain in (decimal)
WCO	Wet basis moisture content of grain out (decimal)

WI	Pounds of water in grain in per hour (lb/hr)
WO	Pounds of water in grain out per hour (lb/hr)
WWR	Pounds of water removed from grain (lb/hr)

INTRODUCTION

A wide variety of farm crops has been artificially dried in the past with satisfactory results for certain uses of those crops. Corn in particular has been artificially dried because of high initial moisture content. A great percentage of the corn (greater than 80%) is used for animal feeds where the nutritional characteristics remain acceptable even though some indices of quality, especially germination, may be quite low as a result of drying. This thesis is concerned with soybeans and the quality retained through artificial drying with a concurrent flow dryer. The soybeans are not intended for use as seed but germination is used as a quality indicator because of its extreme sensitivity. The primary purpose of the drying process is to prepare the soybeans for an oil extraction plant. The high temperatures could have a detrimental effect on the quality of oil extracted from the soybeans. The literature available tended to indicate that about 175° F (79 C) is the upper temperature limit for retaining the oil quality within an acceptable range (Bunn, 1970). Nowhere, was the duration of time and temperature during the drying process linked to quality of the oil.

Soybeans may be stored safely for several months at a moisture content of 13% wb. (Wolf and Cowan, 1971). Prior to processing for oil, however, the moisture content must be reduced to 9% wb.* The first processing step removes the hulls (since they contain no oil) and the second step forms the soybeans into flakes to hasten the solvent extraction rate. This research is concerned with quality changes as the result of drying soybeans between 13 and 9% wb.

The remainder of the soybeans after extraction may be used for soybean meal, soy flours, concentrates, or isolates. These products are used directly as feed (soybean meal), processed further for use as additives to such foods as baked goods for the control of fat absorbtion and emulsification properties, or to produce textured vegetable proteins (Alden, 1975).

The oil quality is the most difficult to retain so it is the quality and retention of the oil quality that is studied in this thesis.

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*Interview with C. M. Westlaken, Westlake Agricultural Engineering, St. Mary's, Ontario, 1977.

BACKGROUND INFORMATION

Crop dryers used for drying seeds, either grains, such as corn, wheat, and oats, or legumes such as soybeans may be of either batch or continuous-flow design. Grains and legumes are two different products but in this thesis for the purposes of description of dryers the term "grains" will include both groups unless specifically indicated otherwise.

Batch drying systems may involve either in-bin arrangements or columns of grain through which air of below 70% relative humidity is forced. Relative humidity of the air is critical because differences in vapor pressure of the water in the air and the water in the kernel determine whether or not drying occurs. This principle holds for all dryers. Equilibrium moisture content is the moisture content of a grain at a specified air relative humidity and temperature. When drying air has a lower relative humidity than that required for the desired final moisture content it is possible that part of the grain bed may be overdried if exposed to that air for a long period of time. Such is the case with many batch systems. Briefly, in a drying bed, a front passes through in the direction of airflow with relatively dry grain as the drying air enters the bed and wet grain beyond. It is possible under conditions where the grain initially is quite cool to have condensation of water on the wet grain side of the front as it passes through the bin.

The in-bin arrangements may use either a full bin, a single layer of a few feet, or several layers added daily on top of each other. Close management is required with each to be sure that the wet grain, not yet reached by the drying front does not remain in the bin long enough for mold to grow. As the depth of grain in the bed increases to a full bin it becomes increasingly important that the equilibrium moisture content of the grain at the drying air conditions is not below the maximum desired final moisture content. Frequently with full bin systems, the grain is stored in the same bin. Therefore the drying front must be forced completely through the bed to prevent mold at the drying front and in the wet grain beyond. Using drying air with a low equilibrium moisture content results in an entire bin of grain that is too dry. This may result in a longer storage life but also in loss of weight for which a premium is not often paid at the market.

With in-bin systems using layers of only a few feet the drying front may not be pushed completely through the bed before drying is stopped. The grain at the air entry point is overdried and the grain on top of the bin remains at a high moisture content. Seldom can this grain be stored safely in the drying bin. By experience the operator can determine how far through the bed the drying front must go so that when the grain is unloaded from the bin and mixed, it will have an average moisture content equal to the desired final moisture content. Several problems here include the breakage that occurs through handling of the overdried grain before mixing, stress cracks in the overdried grain, and if mixing is incomplete the mold that develops in wet pockets.

Uniform filling of the bin is critical to assure an even bed depth and no concentrated areas of broken kernels and foreign materials which may cause uneven airflows and therefore uneven movement of the drying front through the bed. In an effort to reduce the moisture content gradient across the drying front, several manufacturers have developed grain circulation systems to stir the bed continuously. The stirring mechanisms cause local concentrations of foreign material which reduce the uniform flow of air. Such systems have problems with the grain at the air inlet of the bed being subjected to over drying and extended periods of heat. Less than uniform airflows result in the drying front being completely through certain areas of the bed while barely starting in others. Ranges in moisture content result in some moldy areas even though the average moisture content may have been low enough for satisfactory storage. Batch in-bin systems use bed depths of several feet (1 meter).

Batch drying systems using columns generally use higher airflows than the in-bin systems and have vertically oriented bed depths of 12 to 18 inches (30.5 to 45.7 cm) with air passing horizontally. Unfortunately with this system considerable quality damage occurs because of the rapid drying with air of a continuously low relative humidity. With this arrangement more uniform mixing occurs during unloading and this system is easily adapted to automatic cycling so little time is wasted between unloading of a dried batch and refilling with wet grain. At this point also note that the periodic cycling of these large quantities of grain with several hours between cycles warrants extreme caution concerning bystanders who may identify supply bins (garner bins) as having stationary beds. This author feels the operator should watch the operation closely enough to protect outsiders from these less than obvious hazards.

The column type batch dryers are usually not as energy efficient as the in-bin dryers especially where deeper beds are used with the in-bin arrangements. With deeper beds the air will absorb more moisture as it passes through.

Continuous flow dryers are generally of crossflow design. They differ from the batch dryers in that instead of a stationary bed during drying process there is a slowly moving bed of grain. The first most obvious difference is that a grain metering device is required so that the grain flow rate can be regulated and controlled. The grain flow rate is reasonably predictable and constant at any given control setting (Hall, 1957).

Continuous flow crossflow dryers have similar quality problems to those of the batch crossflow design. Over drying on one side of the bed occurs but mixing on release of the grain from the dryer eliminates wet pockets in storage. Personal safety is not quite the problem with continuous flow dryers because all of the grain is continuously moving at the same rate with no sudden changes.

Counterflow continuous-flow dryers are arranged such that the drying air moves up through the bed while the grain is continuously moving downward. The bed is solid, not fluidized, but it is moving. The problem here is that the hottest driest air is exposed to the warmest driest grain. Counterflow dryers cause an extreme gradient of moisture content within individual kernels. Quality may be adversely affected. The kernels will be over dried on the outside but quite wet in the middle. The grain temperature may also approach the initial drying air temperature.

The concurrent continuous flow dryer is the type of dryer studied for use in drying soybeans. Grain flow and airflow both move downward. This creates a situation where the hottest driest air hits the coolest wettest grain. Temperature of the drying air decreases rapidly because it is absorbing moisture from the cool wet grain. The grain temperature also increases rapidly but it never reaches the initial drying air temperature in this dryer. The grain and air temperatures approach each other a few centimeters into the bed and continually decrease from that point. During this temperature decrease tempering occurs where moisture from the center of the individual kernels migrates to the outer kernel parts from where it is slowly absorbed by the drying air. Since the drying air becomes more saturated as the grain moves downward and continues drying reduced stress within the kernels exists than that found in either crossflow or counterflow dryers because of the moisture content gradient. Because of the lower stresses and the fact that none of the grain is exposed to high temperatures for more than a few minutes, significantly higher quality grain can be obtained from this dryer than from crossflow, counterflow, batch crossflow, or certain of the batch in-bin systems while retaining the high capacities associated with continuous flow processes (Brooker et al., 1974).

OBJECTIVES

The objectives of the research reported in this thesis are:

1. To mechanically test a pilot scale concurrent dryer.

2. To test soybeans in a pilot scale concurrent dryer.

3. To analyze quality changes of soybeans dried in a concurrent dryer.

4. To compare results of corn dried in a concurrent flow dryer with those of soybeans.

REVIEW OF SELECTED PREVIOUS CONCURRENT DRYER WORK

Carrano (1970) dried corn with a concurrent flow dryer using a bed depth of only 18 inches (46 cm) and immediately cooled the grain with ambient air in counter-current flow. Both Carrano (1970) and Anderson (1972) in corn (with temperatures up to 550° F, 288 C) and soybeans have maintained a spreading device was necessary to obtain uniform treatment of the grain at the surface of the concurrent bed. The spreading device is a mechanical apparatus that operates either by oscillating or rotary motion to add another thin layer of wet grain about every 20 seconds to the top of the bed. The research reported in this thesis indicated that a grain spreading device is not essential to maintain quality if uniform flow of air and grain is established within the dryer. This is simply a flow design problem. No kernels were found with this design to have been scorched.

Carrano (1970) reported no figure on how much moisture was removed by the cooler but suspected it was relatively low. It is nearly impossible to obtain accurate moisture content readings on samples taken prior to cooling due to handling problems with the warm grain and the moisture content gradient within the kernels.

Exhaust air humidities are difficult to measure as Carrano (1970) reported and it will be discussed in detail later in this thesis. He also discusses the problem of rotary airlocks for moving the grain in and out of the airflow. They may be a problem as experience on this project has indicated. For that reason the rotary airlocks were eliminated in the final design of this project.

Gygax et al. (1974) used higher air temperatures (500° F, 260 C) in a concurrent flow dryer and found a "case hardening" effect that seemed to decrease rather than increase test weight after drying. After re-wetting corn and redrying it with the concurrent flow dryer, some of the decrease may have resulted from the re-wetting. The effects Gygax et al. (1974) reported concerning the operator on counting of stress cracks in a sample is a strong indication of the subjectivity of stress crack analysis. However, this test should be considered with soybeans because of its importance at the time of sale for farmers. Little attention to this factor is generally given for corn.

QUALITY TESTS USED ON THE SOYBEANS

The soybeans which were dried are intended for an oil extraction plant and therefore oil quality is of prime consideration here. Soybean oil is a compound primarily composed of triglyceryl esters of oleic, linoleic, and linolenic acids (Overhults et al., 1972). Fats are generally considered as solidified compounds and oils as liquids depending on the ambient temperature of the particular geographical location (Mehlenbacher, 1960). For convenience the term oils will include both fats and oils.

As indicators of soybean oil quality, Overhults et al. (1972) used free fatty acids, iodine number, peroxide number, and thiobarbituric acid value. Free fatty acids occur as a result of hydrolysis of some of the triglycerides (Mehlenbacher, 1960). Cracks in the soybeans expose the oil to enzmes within the seed. Hydrolysis of the oils (by enzyme action) result in the formation of free fatty acids. During one step of the oil refining process, alkali is added which combines with the free fatty acids. The soap formed by the combination of alkali and free fatty acids percipitates out but carries with it some of the neutral oil. Free fatty acids are therefore undesirable in the crude oil because a lower refined oil yield is realized and the expense of additional alkalis required during processing is a significant expenditure. The free fatty acid results are expressed as oleic assuming the same molecular weight as oleic. The difference, if any, is not significant with such a low acidity. Iodine number concerns oils having only isolated double bonds and indicates total unsaturation (Mehlenbacher, 1960). It is a measure of extreme damage to the oil that is not likely to happen in a dryer. If several of the more sensitive tests show that damage as likely, it could have been used. The peroxides have customarily been considered as products of initial fat decomposition (Mehlenbacher, 1960). The peroxide value units indicate the reactive oxygen content as milliequivalents of oxygen per kilogram of oil or as millimols of peroxide per kilogram of oil. One millimol of oxygen equals two milliequivalents of peroxide. Thiobarbituric acid value was not used because its utility and reliability in this application were not established. Anisidine test could have been used if severe damage had occurred because it is a measure of secondary oxidation in oils. This damage was not indicated by the earlier tests.

The Department of Food Science at Michigan State University conducted the peroxide value test according to the American Oil Chemists' Society (AOCS) Official Method

Cd 8-53 as listed in Appendix B of this thesis. Free Fatty Acids were determined also according to the AOCS Official Method Ca 5a-40 as corrected in 1972 with minor changes as listed also in Appendix B.

The oil was extracted by Soxhlet extraction using hexane as the solvent (Dokhani, 1977). There was some concern that rapid drying of the beans may affect the internal structure and result in a change in the oil yield* (Rodda, 1974; Overhults et al., 1972). To obtain a more accurate indication of oil yield therefore, anhydrous ethyl ether was used as the solvent (Dokani, 1977) according to the official methods of analysis of the Association of Official Agricultural Chemists for Crude Fat Determination of Soybean Samples as also listed in Appendix B of this Thesis. The ether recovers a higher percentage of the oil from the soybeans than the hexane but presents some laboratory problems; therefore, it was not used for all of the extractions.

Germination is a very sensitive indicator of heat damage. Previous corn experience with this dryer has consistently shown retention of at least some of the germination when the corn was not rewetted for testing of multiple passes. To retain germination in grains used for seed, the maximum grain temperatue would certainly have to

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*Interview with Dr. Charles Stine, Department of Food Science, Michigan State University, February 1977.

be lower than those used here. These soybeans are not for seed. However, germination at whatever level to which it is lowered is still a heat damage indicator. It is used as a quality indicator with that fact in mind. Germination samples were each of 100 kernels arranged on absorbent paper, rolled up in waxed paper, with distilled water, and stored at approximately 80°F (26.7 C) for a minimum of 7 days. Only normally sprouted seeds were counted as germinated.

When farmers sell soybeans, the number of split beans is used in the market place as a quality indicator. This is due to the shorter storage life for soybeans which are cracked or split. Apparently the seedcoat, when intact, does offer some protection from rancidity of the oil and from mold growth. For the anticipated use of this dryer as preparation of the soybeans for immediate processing, the absolute amount of cracked and split kernels is not of great concern. A crack is any fissure in the surface and a split is broken pieces. Since the next processing step involves physical crushing of the soybeans to remove the hulls, breaking of the kernels prior does not have a detrimental effect. In fact, it may be beneficial to the process.* Breakage does indicate the stress placed on the individual kernels so this analysis was also conducted.

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*Interview with C. M. Westelaken, Westlake Agricultural Engineering, Inc., St. Marys, Ontario, January 1977.

The samples for both germination and stress cracks were conditioned for a minimum of one week so that all samples would be at the same moisture content and subject to the same amount of drying. Saturated salt solutions of sodium chloride giving a relative humidity of 75% (Hall, 1957) at 80°F (26.7 C) were used to condition the first run samples. An Aminco Aire unit was used to give the same atmospheric conditions for the second run samples. The Amino Aire unit uses a water bath and spray apparatus to establish the dew point temperature. Electric heaters control the dry bulb temperature. The moisture content of the samples after conditioning was 10.7% wet basis.

TEST PROCEDURE

A uniform lot of soybeans raised from certified SRF 200 seed by a Mason, Michigan, farmer was used for the tests. The beans had been stored in a steel bin with aeration until February (the time of purchase) from the previous harvest season. They were stored in burlap bags inside the Agricultural Engineering Building until after the first test run. Because of the low relative humidity in the building (about 20%) the soybeans were slowly drying. By moving the beans outdoors, placing them in a covered steel bin, and circulating air through the beans during periods of high relative humidity we gently increased the moisture content of our stock supply from about 10.0 to 12.5% for the second run.

Moisture contents of the soybeans were measured using a Steinlite electronic moisture tester. Comparing the Steinlite results to oven dry at 210°F (98.9 C) for 48 hours it was found to be high by an average of 0.068% moisture content wet basis high (s=0.020, d.f.=5). Hall (1957) indicates a standard error for the Steinlite of 0.44%. This is an acceptable accuracy so because of the ease of using the Steinlite over the oven dry method, the Steinlite was used for the moisture contents. Samples were placed in self sealing plastic bags at the time of testing and allowed to come to equilibrium at room temperature for one day before taking moisture content readings.

The Steinlite measures an electrical property (capacitance) of the sample and converts that to moisture content. Grain fresh from the dryer has a higher moisture content in the center of the kernels than at the outside edge. Inaccurate readings indicating a lower moisture content result if this moisture is not allowed to distribute itself uniformly throughout the kernels.

Actual dryer operation involved at least two people. Description of the apparatus appears in Appendix D of this thesis but a short review of the procedure for operation is in order. The concurrent section of the dryer was first filled with dry grain until the micro switches on top indicated that it was full. This required 5.875 bushels (0.2070 cubic meters). All recording instruments were switched on. The fan on the concurrent section was then actuated and the burner was ignited and adjusted to the desired temperature by manual regulation of the LPG pressure. Immediately, the cross auger from the base of the concurrent section was switched on. The shunt wound DC motor powering to auger served as the grain flow rate control. The speed control on the motor control unit was adjusted according to Figure 1 to give the

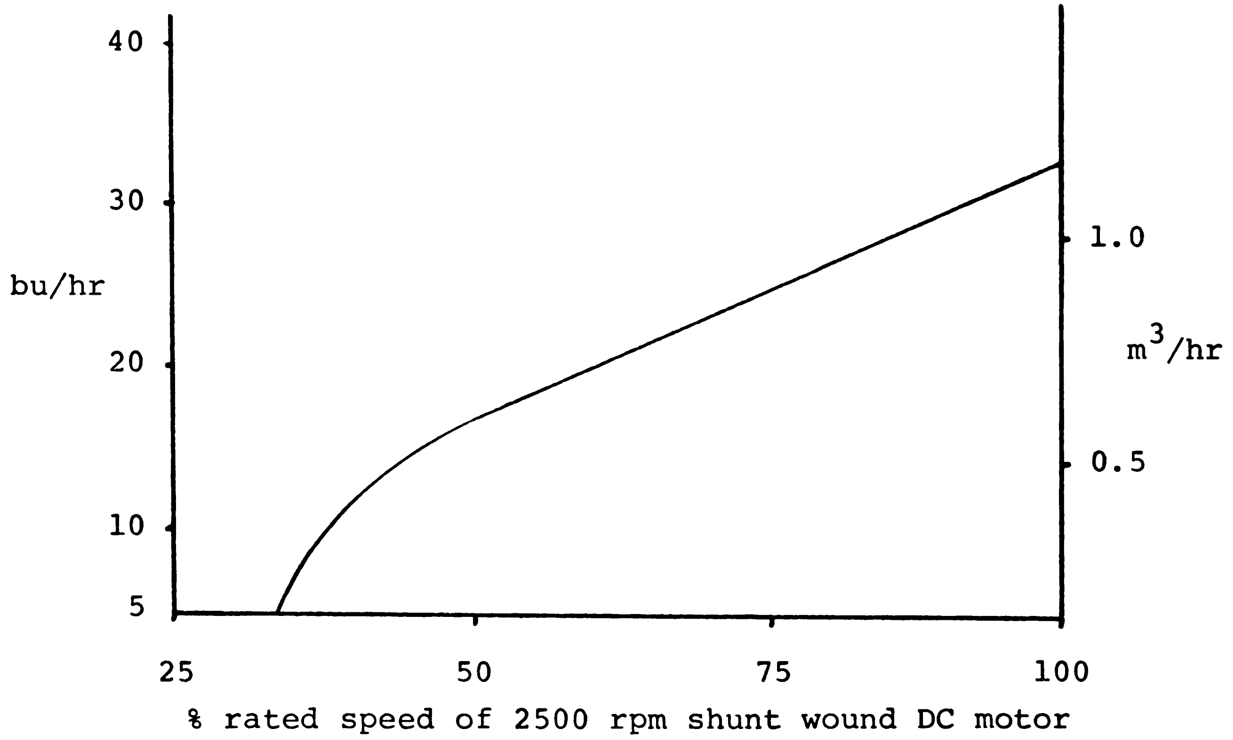

Figure 1.--Grain Flow Calibration Chart.

desired flow rate. Actual flow rates were computed by weighing the entire dryer output during each run. Test beans were then fed in. Steady state conditions were reached at 5.875 bushels (0.2070 cubic meters) when the cooler was not used. An additional 2.362 bushels (0.083 cubic meters) were required to fill the cooler and cross auger. Steady state conditions exist when grain and air outputs stabilize. The dryer was built so that the output from the concurrent section could be diverted from the machine. This gives the capability of using the system as a multi-stage concurrent dryer (with only one concurrent section). Tempering time between passes through the concurrent section is critical to allow moisture to migrate from the middle of the kernels to the outside. In calculating the tempering time it is important to consider also the 2 feet tempering zone at the base of the concurrent section.

Countercurrent cooling was used when the grain flow was not diverted for another pass through the concurrent section as was the case in the second run. The cross auger dumps directly into the cooler.

Together, 2.362 bushels (0.08324 cubic meters) are required to fill both the cross auger and cooler. Microswitches on top of the cooler control the unloading auger at the base so that a constant bed depth is maintained.

Ambient air is used to cool the grain; the cooling fan is turned on when the cooler was full.

Initially, there had been some concern that the entry tube to the concurrent section did not adequately prevent the heated air from escaping out the top. The air movement through the top was in fact insignificant. Two thermocouples located in that tube during the second run (where a heated air temperature of 450°F (232 C) was used) indicated a temperature increase of only 1.25°F (0.7 C) as the grain entered through that tube.

The basic dryer design should permit testing of nearly all common grains such as oats, wheat, rye, corn, soybeans, etc. The slope of 60° on interior grain flow diversion parts is greater than the angles of repose of any of these grains. Even flow of grain through the dryer was not considered as a problem with this system. Although no special attention was given to the problem, no scorched kernels were evident after multiple passes.

RESULTS AND DISCUSSION

Calculation Procedure

A short computer program was developed to assist in evaluation of the individual runs of the dryer. Energy consumption calculation was the primary purpose of the program but it also gives some indication of the experimental technique. The program was written to be run as batch, not online with a teletype. Minor changes would be required for teletype use.

Inputs for each run (or pass) take 3 cards on which the data should be arranged as follows:

Card #1 Each of the following variables may take an F10 field beginning at the left edge of the card (all real numbers).

1 run number
2 temperature of the plenum (°F., F=[(9/5)C] + 32)
3 absolute humidity into concurrent section at ambient temp.
4 dry bulb temperature of ambient air into concurrent section (F)
5 absolute humidity exhausted from concurrent section
6 airflow at ambient of concurrent section (CFM, CFM=cubic meters per minute/0.02831685)
7 density of ambient air into concurrent section [cubic feet per pound, CFP=7.769 (cubic meters per kg)]

Care #2 All real numbers (4 F10 fields from left).

1 run number
2 counterflow section airflow (CFM)
3 absolute humidity of counterflow exhaust
4 absolute humidity into counterflow

Card #3 All real numbers (7 F10 fields from left).

1 run number
2 grain flow rate out (lbs per min, PM=2.2046kg per min)
3 moisture content wet basis of grain in (decimal)
4 moisture content wet basis of grain out (decimal)
5 temperature of grain in (F)
6 temperature of grain out (F)
7 test weight of grain out (lbs per bu, PB=0.7769kg per m^3)

End of data type "0.5" in first 10 spaces of separate card

The calculations assume LPG to have 19,444 BTU per pound (1.800 kg cal/kg), air to have a specific heat of 0.25 BTU per lb °F (0.0002390 J per kg K), and the air density to be the same going into both the concurrent and counterflow sections. Changes in the energy held by the grain in and out use the specific heat equations from Kazarian (1962). As the LPG burns it is assumed to add 1.63 pounds of water to the air per pound of gas burned (Perry, 1973).

More than one set of conditions may be analyzed during a computer run. Each set of 3 cards must have the number of the run (whole real number) in the first 10 spaces of each set of cards. The only end of data card is placed at the end of the entire data stack. No two consecutive runs may have the same run number. Individual run labels are printed as whole numbers only.

If the cooler is not used, card #2 of the run should read as follows:

Card #2 All real numbers (4 F10 fields from left).

1 run
2 0.0
3 absolute humidity into concurrent at ambient
4 absolute humidity into concurrent at ambient

This may be used if an analysis of the individual steps of a multistage run is desired. There is no provision to analyze an entire multistage run as one unit in this program. The individual stages must be entered as separate runs.

Because cross-sectional area figures do not enter into the program, it may be used for other concurrent dryers in the field of any cross sectional area. The program output consists of the following:

1. all input data
2. water removed from the grain per hr*
3. water removed by the air per hr*
4. airflow in concurrent section (lbs per hr)
5. grain flow rate out (lbs per hr)
6. change in grain energy due to difference in temperature and moisture content in and out
7. net energy into system (total minus change in grain energy)
8. total energy into the system (based on airflow, LPG burned, and specific heat of air)
9. LPG burned (based on total energy)
10. energy used to remove water from the grain
11. water removed from the grain (lbs per bushel)

The following output is used if the counterflow cooling section is used:

12. water removed in the concurrent section by the air
13. airflow in the counterflow section (lbs per hr)

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*These two items vary from equality only by measurment error.

The program has assisted in the analysis because fewer hand calculations are required. The program is listed in Appendix A.

The calculations for one run are shown also. This data is from a corn run (2-22-77) that will be referred to later. The cooler was used in this example.

ambient dry bulb temperature
TDBI 58°F
14.4 C

absolute humidity into concurrent section
AHIO 0.007 lb per lb*

airflow in concurrent flow at ambient
AIRH 135 CFM**
3.82 cubic meters per min.

ambient air density
CFP 13.7 cubic ft per lb*
1.76 cubic meters per kg

heated air temperature
TH 400° F
204 C

absolute humidity of concurrent flow exhaust
AHO 0.075 lb/lb*

airflow in counterflow
AIRC 21.CFM**
0.59 cubic meters per min.

absolute humidity of counterflow exhaust
AHOC 0.038 lb/lb

grain flow rate out
PM 5.06 lb/min
2.30 kg/min

moisture content in wet basis
WCI 0.2377 decimal

moisture content out wet basis
WCO 0.1551 decimal

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*Obtained by use of standard ASHRAE psychrometric charts.

**Obtained by pressure drop across laminar flow element.

grain temperature in

TI   42. °F

5.6 C

grain temperature out

TO   64. F

17.8 C

test weight out

BDO   50 lb/bu

644 kg/cubic meter

absolute humidity into cooler

AHIC   0.007 lb/lb*

Example calculations:

TOT (grain flow rate out) = PM*60 (min/hr)
= 5.06*60=303.6 lb/hr
137.7 kg/hr

CAP (grain flow rate out) = 303.6 (lb/hr)/BDO
= 303.6/50
= 6.07 bu/hr
0.214 cubic meters/hr

DM (dry matter = TOT*(1-WCO)
= 303.6*(1-0.1551)
= 256.5 lb/hr
116.3 kg/hr

WI (pounds of water in grain in per hour)
= WCI*DM/(1-WCI)
= 0.2377*256.5/(1-0.2377)
= 79.98 lb/hr
36.29 kg/hr

WO (pounds of water in grain out per hour)
= WCO*TOT
= 0.1551*303.6
= 47.09 lb/hr
21.36 kg/hr

WWR (pounds of water removed from grain per hour)
= WI-WO
= 79.98-47.09
= 32.89 lb/hr
14.93 kg/hr

---

*Obtained by use of standard ASHRAE psychrometric charts.

```
TGE (change in energy of grain due to changes in tempera-
     ture and moisture content in and out)
               = TO*[.35 + (.851)*WCO] *TOT-TI*
                 [.35 + (.851)*WCI] *WI/WCI
               = 64.* [.35 + (.851)*0.1551]*303.6-42.*
                 [.35 + (.851)*0.2377]*79.98/0.2377
               = 1560.4 BTU/hr
                 1646300. j/hr

PH (pounds of dry air per hour through concurrent section)
               = AIRH*60./CFP
               = 135.*60./13.7
               = 591.2 lb/hr
                 268.2 kg/hr

AHI (aboslute humidity of air into dryer after heating)
               = AHIO + (TH-TDBI)*(.25 BTU/lb F)
                 (lb.LPG/19444 BTU) (1.63 lb water/lb LPG)
               = 0.007 + (400.-58)*0.25/19444*1.63
               = 0.0142 lb/lb

AHRA (pounds of water removed by air in the concurrent
      section per hour)
               = (AHO-AHI)*PH
               = (0.075-0.0142)*591.2
               = 35.94 lb/hr
                 16.30 kg/hr

PHC (airflow in cooler)
               = (AIRC/CFP)*60
               = (21./13.7)*60
               = 92.0 lb/hr
                 41.7 kg/hr

AHR (pounds of water removed by the air in both sections)
               = AHRA + (AHOC-AHIC)*PHC
               = 35.94 + (0.038-0.007)*92
               = 38.79 lb/hr
                 17.60 kg/hr

BTU (net energy into system)
               = (TH-TDBI)*0.25*PH-TGE
               = (400-58)*0.25*591.2-1560.4
               = 48987.2 BTU/hr
                 51684200. j/hr
```

GBTU (gross energy into system)
= BTU + TGE
= 48987.2 + 1560.4

= 50547.6 BTU/hr
53330500. j/hr

PRO (propane burned per hour)
= GBTU/19444
= 50547.6/19444
= 2.60 lbs/hr
1.18 kg/hr

BTUPP (energy consumed per pound of water removed)
= BTU/WWR
= 48987.2/32.89
= 1489.4 BTU/lb
827.44 kg/cal/kg

WBU (water removed from grain)
= BDO*WWR/TOT
= 50.*32.89/303.6
= 5.417 lb/bu
6.9 kg/cubic meter

In comparing the above calculated values to those found in the computer output shown in Appendix A for corn of 2/22/77 the answers are quite close. The differences are due to rounding off errors in the longhand calculations. Two corn runs have been included in the appendix to show how the program works. In addition to the one previously mentioned there is also data for corn from 3/8/77. These two runs used the same corn but it was rewetted in between runs with distilled water and allowed to come to equilibrium for a week at 40°F (4.4 C) prior to drying. The water calculated to have been removed by the air and the water calculated to have been removed from the grain should be equal. If these two numbers fail to be equal there is a measurement problem somewhere. For the February run the grain to air water removal ratio was 32.90/39.06 or 0.84. For March it was 46.76/42.02 or 1.11. These values are both reasonably close to 1.00. At least close enough to consider the measurements used to calculate those values (airflows, humidities, moisture contents, and grain flow rates) as within an acceptable range. Keep in mind that here are large changes in moisture contents during drying and quite high exhaust air relative humidities. Humidities were measured using wet and dry bulb thermocouples that would only indicate relative humidities too high. Inadequate wet bulb depression results from insufficient air velocity or improper design and location.

Several observations can be made concerning the results to be expected when using rewetted grain (corn in particular). The test weight dropped, concurrent airflow increased, and the energy consumed per pound of water removed decreased. Physical breakdown of the kernel structure is likely to be the cause of the energy consumption decrease. This suggests the use of artificially rewetted corn for research data may be less than desirable from a standpoint of accuracy.

Soybean Test Data

A "run" is one complete processing cycle on a quantity of soybeans. A "pass" is that part of the cycle where the soybeans go through the concurrent section once. On 2/4/77 the first run was made and an attempt to acquire data on two passes was only partially successful. The 3/15/77 run was a single pass. In Appendix A three sets of soybean data are listed. For 2/4/77 the first run first pass and first run second pass are listed. For 3/15/77 only one pass was conducted so only one set of results is relevant. A time schedule of when each grain sample was organized when data for each pass was collected and assisted in determining when steady state operating conditions were reached. As mentioned earlier, 5.875 bushels (0.2070 cubic meters) are required to fill the concurrent section. Since in the first run the grain flow rate was 588 lb/hr (266.7 kg/hr) with a test weight of 57 lb/bu (734 kg/cubic meter) steady state was reached in 34.2 minutes. The cooler was not used in the test. Also to be considered is the fact that a pass of grain into the dryer takes 34.2 minutes to mass through. The last input sample was deleted from the analysis because it was not typical in relation to the other values and no output samples were taken at 34.2 minutes. For the input moisture content (wet basis) of the first run-first pass of 13.6% the sample standard deviation(s) was 0.12 with 3 degrees of freedom (d.f.). Output samples were collected from the dryer spout and sealed in plastic bags also. The warm grain was not allowed to exchange moisture with the ambient air. The average output moisture content of the first run first pass was 11.4% with a s=0.43 and d.f.=4.

Between passes the grain was tempered for approximately 35 minutes. Additional samples were taken as this first pass output grain was fed into the dryer as input second pass grain. The surfaces of the containers were exposed to ambient air for a time and it is possible that some moisture, at least from the container surfaces may have evaporated to the air from the war grain during this period. The samples were taken from the surface. They indicated a lower moisture content (0.6% MC wb) than the samples taken at the output spout. Those samples were therefore not included in the analysis.

Output moisture content of the first run-first pass was used as the input to the first run second pass. The output to the first run second pass posed other difficulties. An error predicting when steady state conditions of the output would occur resulted in termination of sampling too soon. Referring to the times of sampling schedule, and the fact that at 588 lb/hr (266.7 kg/hr) 34.2 minutes are required to reach equilibrium, there was only one valid output sample. The sample was collected only one minute after equilibrium had been established. Basic statistics would not put much value on a single sample but it is in the likely range and had to be used for the inferences to be made from this analysis.

Data collection for the second run (3/15/77) was more consistent. It was a single pass run and the cooler was used. For the inlet moisture content of 12.5% wb s=0.14 and d.f.=11. The outlet moisture content of 10.6% wb had s=0.16 and d.f.=7. Some additional static pressure data was collected to use as a check on the airflow determined by use of the laminar flow element on the concurrent section. The bed depth in the concurrent section was 3 feet. Several holes were drilled into the wall of the dryer to check the drop in static pressure across the bed. Comparing this pressure drop to Shedd's data (1953) for soybeans an estimation of airflow was obtained. Between the 1 and 2 feet bed depths there was a pressure drop of 1.8 inches (4.6 cm). Interpolation beyond the range of the chart (if this is accurate) gives an airflow of at least 120 CFM (3.40 cubic meters/min) which is in the neighborhood of the 141 CFM (4.0 cubic meters/min) determined by pressure drop across the laminar flow element. Since this interpolation is somewhat questionable the laminar flow element figure was used for the calculations.

The weight of water removed from the grain and the total water removed by the air (grain to air water removal ratio) do not balance for any of the 3 sets of soybean data. For the first run first pass it is 14.97/33.58 or 0.46, for the first run second pass it is 14.27/27.61 or 0.52, and for the second run it is 14.33/35.20 or 0.41. It is apparent that an error of approximately the same magnitude occurred in all 3 cases. The corn data was obtained with the same equipment between when the two soybean runs were made. This indicates that it is likely to be a problem typical to only the soybean runs. In reviewing the accuracy of the measurements, the grain flow rate is correct because total output was weighed and timed. Moisture content error is small as discussed earlier. So the water removed from the grain is probably reasonable. Moving to the airflow measurements, there was airflow through the concurrent section similar to what occurred with corn (123 to 146 CFM at the extremes). Inlet absolute humidities were measured with a Bendix Aviation psychrometer. Outlet absolute humidities were measured through the use of wet and dry bulb thermocouples placed in the 4 inch (10.2 cm) diameter exhaust port of the concurrent section. The airflow across the wet bulb wick according to Brooker et al. (1974) must be at least 15 ft/sec (4.57 m/sec) to obtain maximum wet bulb depression. The mean air velocity through the 4 inch port at 123 CFM (3.48 cubic meters/min.) is only 10.7 ft/sec and at 145.5 is 12.7 ft/sec. Calculation of Reynolds number indicates the air to be in turbulent flow. Therefore, the velocity over the wet bulb wick is nearly equal to the mean velocity. The web bulb temperature was the measurement most likely to be in error because the other measurements are more stable. The other measurements can be used to recalculate the concurrent exhaust humidity and determine what the actual wet bulb temperature was. Carrano (1970) had the same problem with his dryer and used a similar approach in his analysis.

Shown below are the calculations for the first run first pass. Following those calculations Table 1 shows the results of the same series of calculations for all three sets of soybean data. The table shows the calculated wet bulb temperature measurement to have been consistently at least 12.5° F lower than the measured values for the soybean tests.

Threlkeld (1962) has published data showing errors in wet bulb temperature measurement as a result of radiation error and low airflow. Although the wet bulb depression was only 20°F (11. C) and maximum air

TABLE 1.--Humidity Corrections Calculation Example (First Run First Pass).

Conditions	
Drying Parameters	Physical Quantities*
WWR	14.97 lb/hr 6.79 kg/hr
AHIO	0.003 lb/lb
PH	573.1 lb/hr 260.0 kg/hr
TH	350° F 177 C
TDBI	68° F 20 C
Concurrent exhaust dry bulb temperature	152° F 67 C

*Calculations

AHI = AHIO + [(TH-TDBI)*().25)(1/19444)(1.63)]
= 0.003 + [(350.-68.)*(0.25)(1/19444)(1.63)]
= 0.00891 lb/lb

Outlet absolute humidity
= AHI + WWR/PH
= 0.00891 + 14.97/573.1
= 0.0350 lb/lb

temperature only 120°F (49. C) for the data listed in Threlkeld (1962) the trend indicates a maximum wet bulb temperature measurement error due to both radiation and airflow rates to be of only about 0.5°F (0.3 C) for the soybean data presented here. If in fact the error does lie in wet bulb temperature measurement, the error could also result from conduction through the wick to both the distilled water and the thermocouple wire.

Standard errors in the measurements considered as accurate should be examined to see if they can account for the apparent error in wet bulb temperature measurement. Loeffler (1966) indicates the accuracy of iron-constantin thermocouples (type J) to be ± 4.0°F (±2.2 C). Type J thermocouples were used to sense the heated air temperature. Type T thermocouples (copper-constantin) were used through the rest of the dryer and have an accuracy of ± 1 1/2°F (0.8 C) in the temperature range of -75 to 200°F. The Steinlite moisture tester manufacturer states its moisture tester to have an accuracy of ±0.44% MC wb. The platform scale used to weight the output grain is calibrated to an accuracy of ± 1/8 lbs (0.06 kg). With the five weight measurements averaged for the first run, the total error in weight would be ± 5/8 lbs (0.3 kg).

The airflow measurement with the Meriam Laminar flow element and manometer is claimed to be quite accurate. However, to be more realistic in case dirt and bees' wings were present in the cone assembly of the lamimar flow element an accuracy of ± 10 CFM (0.28 cubic meters/ min) will be considered.

Recalculation with all the above standard measurement erros combined gives the following information in relation to the first pass first run soybeans in Appendix A. The weight of water removed from the grain is ± 6.05 lb/hr, total water removed by air is ± 3.66 lb/hr. The net energy figure is ± 4432 BTU/hr, gross energy ± 4961 and energy used to remove water from grain ± 822 BTU/lb. These large cumulative errors may help to explain some of the difference between the weight of water removed from the grain and weight of water removed by the air but do not account for the entire difference. The wet bulb temperature measurement appears to be quite inaccurate.

To acquire information on the temperatures within the concurrent stage of the dryer, three thermocouples were installed through the side at 6 inches (15.2 cm), 1 foot (30.5 cm), and 2 feet (61.0 cm) down into the bed protruding into the bed 1 3/4 inches (4.46 cm). The indicated temperatures are values somewhere between the air and the grain temperatures. Surface conduction heat transfer takes place between the thermocouples and the kernels and convection heat transfer takes place between the thermocouples and the air. The measured data appears later in the thesis.

Bakker-Arkema et al. (1974) have developed a computer simulation model to describe the drying process within a concurrent flow grain dryer. A thin-layer equation must be supplied in the program for the particular product to be dried. For soybeans the Sabbah et al. (1976) thin-layer equation for beans was used. Computer outputs for both the first and second runs are included in Appendix C. In Figure 2 the air and grain temperatures are plotted as curves and the measured temperatures from within the bed as points for the first run-first pass. The maximum measured temperature in the first run first pass was 160°F (71 C) at the 2 feet level. The program predicts a maximum grain temperature of 150.8°F (66 C) but the two peaks occur at different locations. The predicted output moisture content of 11.97% wb is close to the actual value of 11.1% wb. The calculated final air relative humidity was about 3% lower and exhaust air temperature 3 to 21°F (12 C) higher (Table 2).

For the first run second pass, Figure 3 shows predicted air temperature, predicted grain temperature, and measured bed temperatures. Once again the measured values do not appear to fall between the air and grain predicted temperatures. Notice also that the simulation predicted

Figure 2.--Predicted v. Actual Bed Temperatures for the First Run First Pass.

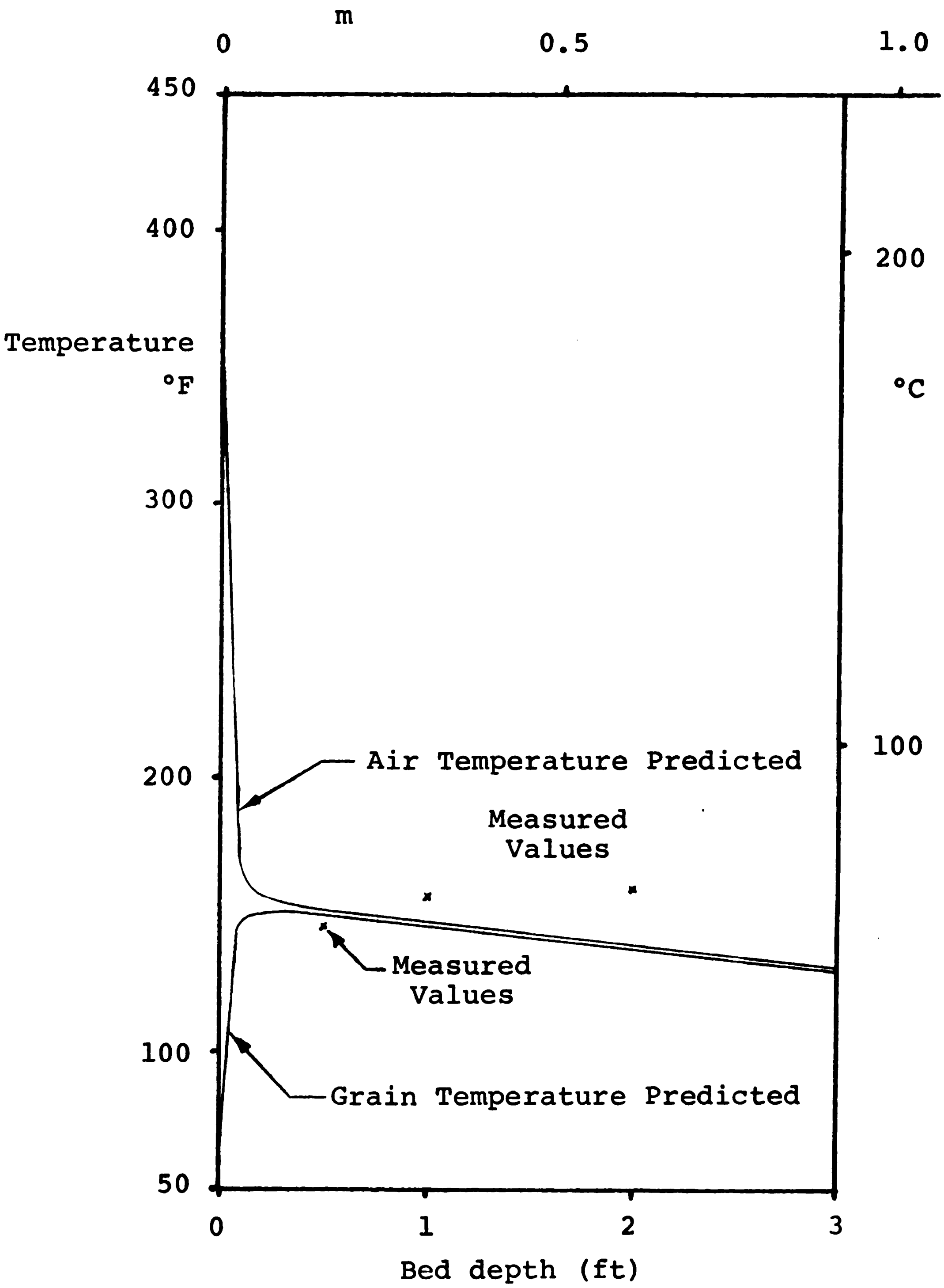

m
0
0.5
1.0
450
400
300
200
100
50
Temperature
°F
200
100
°C
Air Temperature Predicted
Measured
Values
Measured
Values
Grain Temperature Predicted
0
1
2
3
Bed depth (ft)

TABLE 2.--Calculated and Measured Exhaust Wet Bulb Temperatures.

		First run First pass	First run Second pass	Second Run
WWR	lb/hr	14.97	14.27	14.33
	kg/hr	6.79	6.47	6.50
AHIO	lb/lb	0.003	0.003	0.006
PH	lb/hr	573.1	550.7	622.1
	kg/hr	260.0	249.8	282.2
TH	°F	350.	300.	450.
	C	177.	149.	232.
TDBI	°F	68.	68.	74.
	C	20.	20.	23.
Dry Bulb Concurrent Exhaust Temperature	°F	152.	155.	171.
	C	67.	68.	77.
AHI	lb/lb	0.0089	0.0079	0.014
Calculated outlet Absolute Humidity	lb/lb	0.0350	0.0338	0.0372
Calculated Relative Humidity	%	20.	18.	14.
Calculated Wet Bulb Temperature	°F	103.	102.	106.
	C	39.	39.	41.
Measured Wet Bulb Temperature	°F	118.	115.	120.
	C	48.	46.	49.
Error in Wet Bulb Temperature Measurement	°F	+15.	+12.5	+13.5
	C	+ 8.3	+ 6.9	+ 7.5

a 20°F (11 C) higher temperature than was recorded in the experiment. The simulation predicted well on the amount of drying (1.85% to 1.87% wb reduction) but the calculated relative humidity was again higher (by 3%) and exhaust air temperature higher (3°F, 2 C) (Table 2).

On the second run a heated air temperature of 450.°F was used. Figure 4 shows the predicted versus measured temperature values. Peak grain temperatures were in the same are of the bed but predicted grain temperature was 5°F (3 C) too high. The simulation indicates drying of about 0.25% wb more. The calculated exhaust relative humidity (RH) of 14% and temperature of 171°F (77 C) compare favorably with the 16% RH and 150°F (70 C) predicted.

To compare the soybean results with those of corn, the same operating conditions as for the first run first pass soybeans and the conditions of the second run were used. Once again the concurrent dryer simulation was used but this time the Thompson thin-layer equation for corn was used. The output has been included in Appendix C. Corn seems more difficult to dry in the 13% to 9% wb range. However, it is seldom necessary to dry corn below 12% wb. Relative humidity and equilibrium moisture contents determine how dry a product must be for safe storage. Soybeans must be dried to about 10-11%:corn to 14.5-15.5%. As a product dries, the energy required to

Figure 3.--Predicted v. Actual Bed Temperatures for the First Run Second Pass.

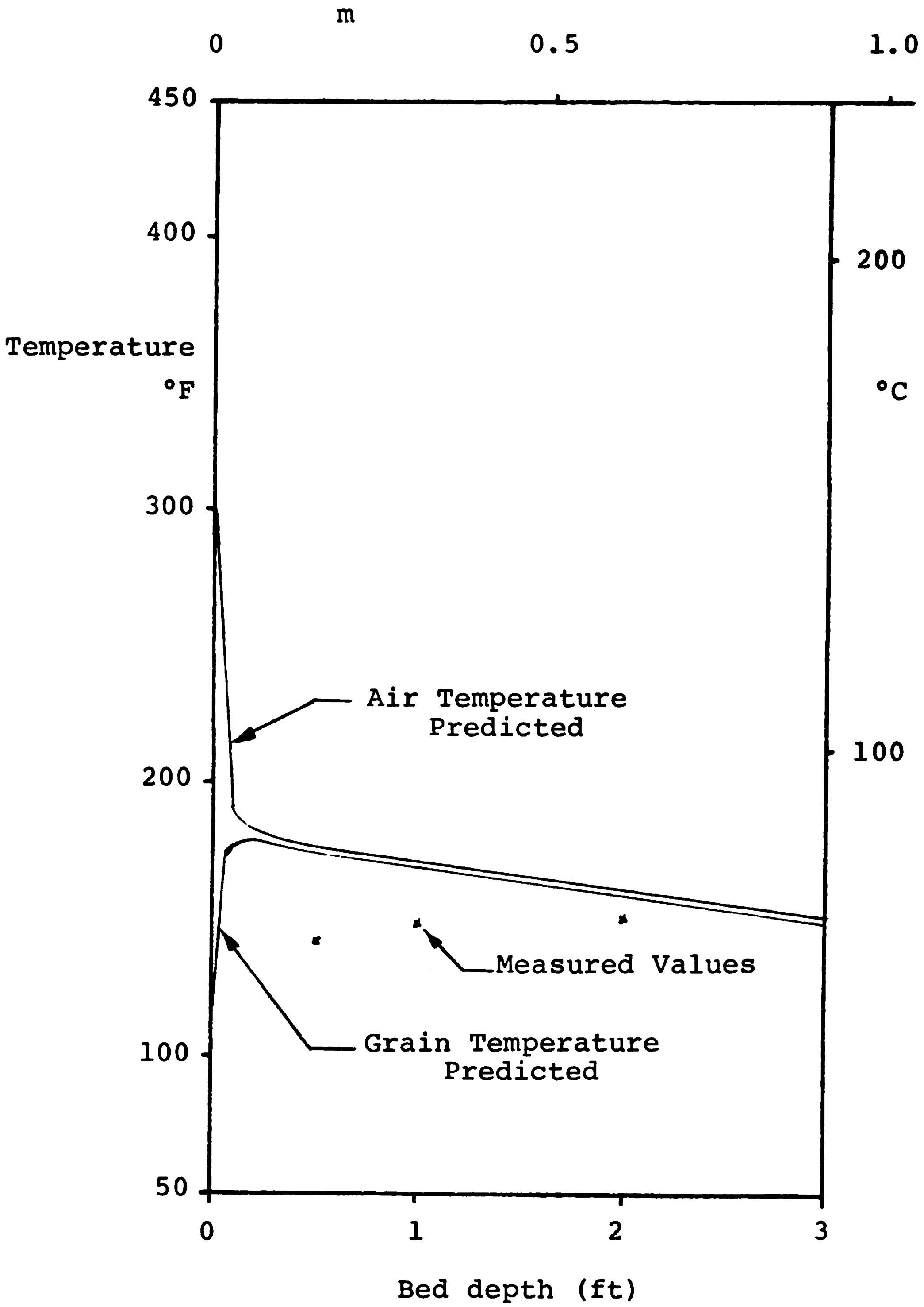
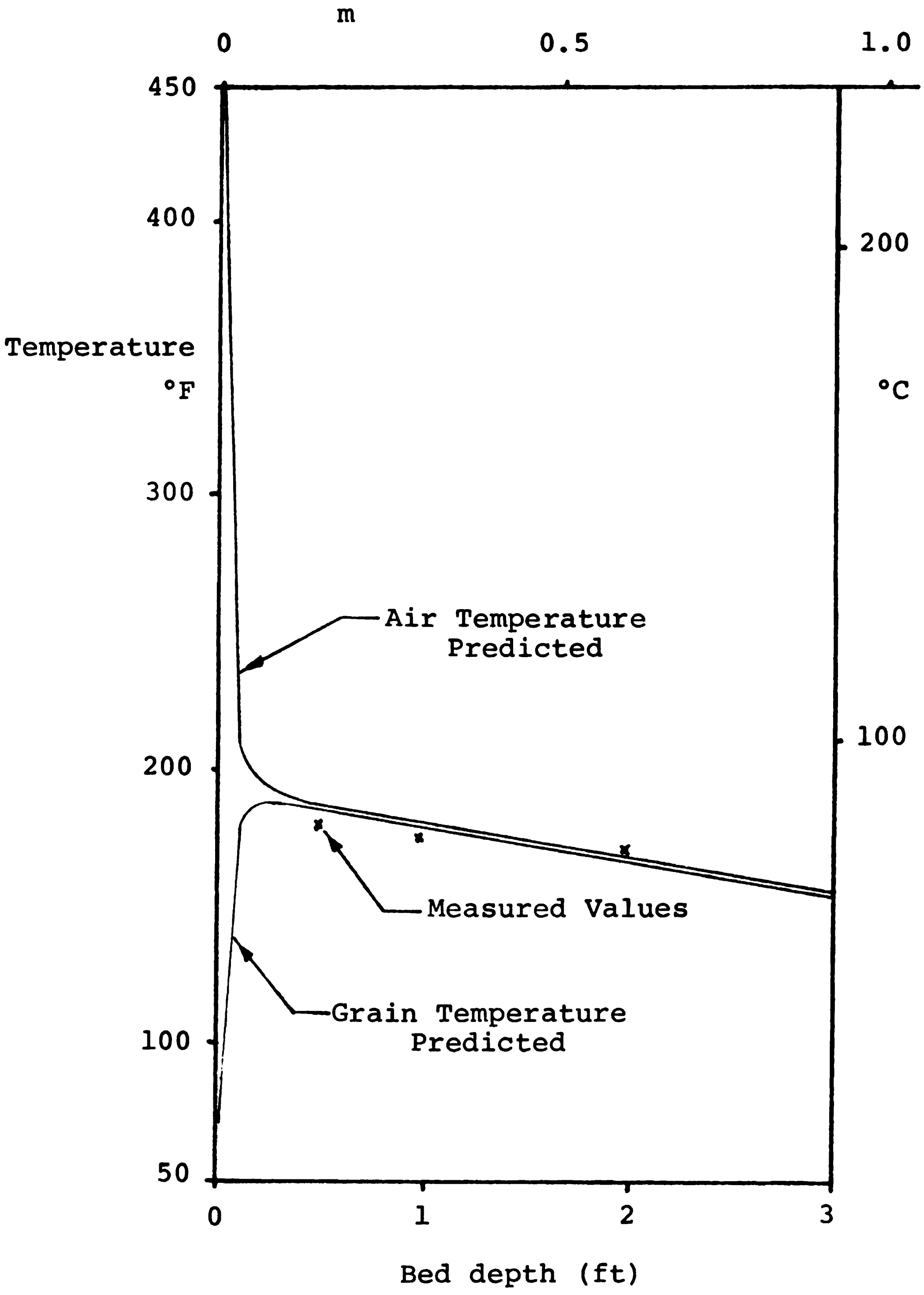

m
0
0.5
1.0
450
400
300
200
100
50
Temperature
°F
200
100
°C
Air Temperature
Predicted
Measured Values
Grain Temperature
Predicted
0
1
2
3
Bed depth (ft)

Figure 4.--Predicted v. Actual Bed Temperatures for the Second Run.


m
0
0.5
1.0
450
400
200
Temperature
°F
°C
300
Air Temperature
Predicted
100
200
Measured Values
Grain Temperature
Predicted
100
50
0
1
2
3
Bed depth (ft)

remove an additional quantity of water increases. In general it is probably more likely that corn will dry more rapidly and with lower fuel requirements because higher final moisture contents may be acceptable. Brook* suggests some differences in drying rates may be due to differences in particle size.

The Sabbah thin-layer equation for beans may have application in the concurrent dryer simulation for prediction of maximum soybean temperatures in the dryer. Unfortunately, there apparently is no temperature and time v. quality data to use for management but the simulation can be used when the information becomes available.

Quality Analysis Results

Germination of the soybeans was above 50% for all samples. For counting of cracks in individual beans (cracks are defined as any fissure in the surface) two operators were used. One for each run. This makes the results between runs somewhat less than absolutely comparable because of the subjectivity of the operators. However, the trends are the same. Table 3 shows germination, cracks, maximum predicted temperatures, maximum measured bed temperatures and heated air temperatures. The method of counting splits, or broken soybean pieces, was not

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*Interview with R. C. Brook, Research Associate, Department of Agricultural Engineering, Michigan State University, March 1977.

TABLE 3.--Concurrent Exhaust Relative Humidity Predicted v. Calculated Values.

	First Run First Pass	First Run Second Pass	Second Run
Air Temperature Measured			
F	152.	155.	171.
C	67.	68.	77.
Relative Humidity Calculated			
%	20	18	14
Air Temperature Predicted			
F	131.	152.	158.
C	55.	67.	70.
Relative Humidity Predicted			
%	22	15	16
Difference Between Measured and Predicted Relative Humidity	-2	+3	-2

accurate enough to be included but few splits did occur. The number of splits was certainly less than 1%.

It is apparent that even though the soybeans may have reached the critical quality temperature of 175°F (79 C) (as indicated by Bunn, 1970) there was no extreme decrease of germination. This indicates that temperature is related to quality but the time at a given temperature is also very important. Referring to the computer simulation, the soybeans were at their maximum temperature for relatively short periods of time. Drying caused only small changes in germination and cracking percentages in the operation planned as one of the early steps in soybean oil extraction. Decreasing the grain flow rate from what was used in the tests will increase the amount of drying but will increase the grain tempertature within the dryer and may adversely affect the quality.

Samples were combined to provide two inlet and two outlet samples per run to be processed for quality by the Food Science Department. Four duplicates of each test were processed. Table 4 shows the results of the analysis.

There was no significant change in quality as measured with the tests after drying of the soybeans in a concurrent flow dryer. The peroxide value would have been the first indicator of deterioration and it remained

TABLE 4.--Germination and Stress Cracks of the Soybean Samples.

	First Run First Pass	First Run Second Pass	Second Run
Heated Air Temperature			
F	350.	300.	450.
C	177.	149.	232.
Maximum Predicted Temperature of Soybeans			
F	156.	181.	192.
C	69.	83.	89.
Maximum Measured Temperature			
F	160.	152.	182.
C	71.	67.	83.
% germination			
before drying	99.	66.	99.
after drying	66.	51.	57.
% cracks			
before drying	2.	18.	1.
after drying	18.	37.	21.

unchanged. The oil quality was superior before as well as after drying (Dokhani, 1977).

Some interior breakdown of the physical soybean structure may have occurred and as a result the allowable storage life may have decreased. Stine* noted that none of these quality indicators would measure such a problem. For use as a dryer in an oil extraction plant, however, storage will likely be only for a very short period. Thus, interior breakdown, if it exists, is not a major concern. If breakdown of the soybeam structure occurres, the oil yield may be favorable affected due to easier extraction; the test did not show a significant change in oil yield.

TABLE 5.--Results of Chemical Oil Analysis.

	First Run First Pass	Second Run
% Crude Fat		
Before drying	18.06	16.88
After drying	18.20	17.14
Peroxide value as milliequivalents of peroxide per kilogram of oil		
Before drying	<0.01	<0.01
After drying	<0.01	<0.01
% Free Fatty Acids as Oleic		
Before drying	0.192	0.176
After drying	0.176	0.205

*Interview with Dr. Charles Stine, Department of Food Science, Michigan State University, February 1977.

CONCLUSIONS

1. Air temperatures of at least 450.°F (232 C) may be used to dry soybeans from 13% to 9% in a concurrent flow dryer without significant reduction of the resulting oil quality provided the flow rate is adjusted to less than 10 bushels per hour square foot (0.032 cubic meters per hour square meter). There is likely to be a limit not far from these values for oil quality to suffer deleterious effects but the limiting temperature, grain flow rate, and moisture content range have not yet been determined.

2. Mechanical leveling devices are not necessary on the concurrent bed surface for introducing the wet grain.

3. It is possible to have a concurrent dryer function effectively without the use of rotary airlocks to control air and grain movement.

4. Instrumentation to continuously monitor moisture content in the dryer would assist in management.

5. The difference in temperature between the inlet cooler air and outlet grain temperature of about 40°F (22 C) probably did not stress the soybeans.

6. Reduction of moisture content in the cooler was not very high.

SUGGESTIONS FOR FURTHER STUDY

Development of instrumentation to accurately record the exhaust air relative humidity and continuously monitor grain moisture content would greatly assist laboratory work in this area. Future work should also include statistical evaluation of drying parameters to find optimum conditions for both energy efficiency and high quality grain output. Computer simulation models predicting output moisture content with changing inlet moisture contents would assist in the management of drying operations.

Quality tests to be considered should include more than those of oil analysis. Protein Dispersibility Index and Nitrogen Solubility Index should be included as measures of heat damage to the protein of the soybeans. Changes in safe length of storage for retention of quality due to any interior structural breakdown should be considered if the dried soybeans are not immediately processed. The relationship of quality to grain flow rate and moisture content decrease should also be investigated.

APPENDIX A

CONCURRENT DRYER ANALYSIS PROGRAM

Listing of the Concurrent Dryer Analysis Program

```
PROGRAM GRAIN     73/73    OPT=1                    FTN 4.6+433        04/15/77 .16.58.13        PAGE     1

        108    PROGRAM GRAIN(INPUT,OUTPUT,TAPE60=INPUT,TAPE61=OUTPUT)
               REAL N
        109    W=0.0
        111    READ112,C,TH,AHIO,TDBI,AHO,AIRH,CFP
        112    FORMAT(7F10.5)
               IF(C.LT.0.5)GO TO 130
               IF(C.EQ.0.5)GO TO 140
        115    N=1.
               W=0
        116    READ117,C,AIRC,AHOC,AHIC
        117    FORMAT(4F10.5)
               IF(C.LT.5)GO TO 130
               IF(C.GT.5)GO TO 130
        118    N=N+1.
        119    READ112,C,PM,WCI,WCO,TI,TO,BOO
        120    IF(C.LT.5)GO TO 130
               IF(C.GT.3)GO TO 130
        121    N=N+1.
        122    IF(N.LT.3.)GO TO 130
               IF(N.GT.3.)GO TO 130
        3      TOT=PM*60.
        6      DM=TOT*(1.-WCO)
        9      WI=WCI*DM/(1.-WCI)
        12     WO=WCO*TOT
        15     WWR=WI-WO
        28     WOO=BOO*WWR/TOT
        29     TGE=TO*(.35+(.851)*WCO)*TOT-TI*(.35+(.851)*WCI)*WI/WCI
        30     CAP=TOT/300
        57     PH=AIRH*60./CFP
        66     AHI=AHIO+((TH-TDBI)*2.09576E-5)
        69     AHWA=(AHO-AHI)*PH
        72     PHC=(AIRC/CFP)*60.
        75     AHWS=AHWA+(AHOC-AHIC)*PHC
        84     STU=(TH-TDBI)*.25*PH-TGE
               CSTU=STU+TGE
        93     PSC=CSTU/1944+4.
        102    STUPP=STU/WWR
               PRINT133
               PRINT133
        133    FORMAT(*-*)
               PRINT135,C
        135    FORMAT(* *,45X,*RUN NUMBER*,F10.0)
        200    PRINT201,TDBI
        201    FORMAT(* *,25X,*TDB AMBIENT*,39X,F10.1,2X,*DEGREES F*)
        202    PRINT203,AHIO
        203    FORMAT(* *,25X,*ABS HUMIDITY IN*,35X,F10.5,2X,*LB PER L3*)
        204    PRINT205,AIRH
        205    FORMAT(* *,25X,*AIRFLOW IN CONCURRENT FLOW AMBIENT*,16X,F10.1,2X,*
              1CFM*)
        206    PRINT207,CFP
        207    FORMAT(* *,25X,*AMBIENT AIF DENSITY*,31X,F10.2,2X,*CUBIC FT PEP LB
              1*)
        208    PRINT209,TH
        209    FORMAT(* *,25X,*HEATED AIR TEMP*,35X,F10.1,2X,*DEGREES F*)
        210    PRINT211,AHO
        211    FORMAT(* *,25X,*ABS HUMIDITY CONCURRENT FLOW EXHAUST*,14X,F10.5,2X
              1,*LB PER L3*)
               IF(AHOC.GT.AHIO)GO TO 212
               GO TO 216
        212    PRINT213,AIRC
        213    FORMAT(* *,25X,*AIRFLOW IN COUNTERFLOW*,28X,F10.2,2X,*CFM*)
        214    PRINT215,AHOC
        215    FORMAT(* *,25X,*ABS HUMIDITY COUNTERFLOW EXHAUST*,13X,F10.5,2X,*LB
              1 PER L3*)
        216    PRINT217,PM
        217    FORMAT(* *,25X,*GRAIN FLOW OUT*,36X,F10.3,2X,*LB PER MIN*)
        218    PRINT219,WCI
        219    FORMAT(* *,25X,*MOISTURE CONTENT WB IN*,29X,F10.4,2X,*DECIMAL*)
        220    PRINT221,WCO
        221    FORMAT(* *,25X,*MOISTURE CONTENT WB OUT*,27X,F10.4,2X,*DECIMAL*)
        222    PRINT223,TI
        223    FORMAT(* *,25X,*GRAIN TEMPERATURE IN*,30X,F10.1,2X,*DEGREES F*)
        224    PRINT225,TO
        225    FORMAT(* *,25X,*GRAIN TEMPERATURE OUT*,29X,F10.1,2X,*DEGREES F*)
        226    PRINT227,BOO
        227    FORMAT(* *,25X,*TEST WGT OUT*,38X,F10.1,2X,*LBS PER BU*)
        228    PRINT229,WWR
```

```
      229  FORMAT(*-*,25X,*WGT OF WATER REMOVED FROM GRAIN*,19X,F10.2,2X,*LB
          1PER HR*)
           IF(AHOC.GT.AHIO)GO TO 230
           GO TO 232
      230  PRINT231,AHPA
      231  FORMAT(* *,25X,*WATER REMOVED IN CONCURRENT SECTION BY AIR*,8X,F10
          1.2,2X,*LB PER HR*)
      232  PRINT233,AHR
      233  FORMAT(* *,25X,*TOTAL WATER REMOVED BY AIR*,24X,F10.2,2X,*LB PER H
          1R*)
      234  PRINT235,PH
      235  FORMAT(* *,25X,*AIRFLOW IN CONCURRENT SECTION*,21X,F10.1,2X,*LB PE
          1R HR*)
           IF(AHOC.GT.AHIO)GO TO 236
           GO TO 238
      236  PRINT237,PHC
      237  FORMAT(* *,25X,*AIRFLOW IN COUNTER CURRENT SECTION*,16X,F10.1,2X,*
          1LB PER HR*)
      238  PRINT248,CAP
      248  FORMAT(* *,25X,*GRAIN FLOW RATE OUT*,31X,F10.2,2X,*BU PER HR*)
      239  PRINT249,TCT
           PRINT 250,TSE
      250  FORMAT(* *,25X,*ENERGY CHANGE DUE TO TEMP AND MC IN AND OUT*,7X,F1
          10.1,2X,*BTU PER HR*)
      240  PRINT 241,BTU
      241  FORMAT(* *,25X,*NET ENERGY INTO SYSTEM*,28X,F10.1,2X,*BTU PER HR*)
           PRINT 251,GBTU
      251  FORMAT(* *,25X,*GROSS ENERGY INTO SYSTEM*,26X,F10.1,2X,*BTU PER HR
          1*)
      242  PRINT243,PFO
      243  FORMAT(* *,25X,*PROPANE BURNED*,36X,F10.3,2X,*LB PER HR*)
      244  PRINT245,BTUPP
      245  FORMAT(* *,25X,*ENERGY USED TO REMOVE WATER FROM GRAIN*,12X,F10.1,
          12X,*BTU PER LB*)
      246  PRINT247,WBJ
      247  FORMAT(* *,25X,*WATER REMOVED FROM GRAIN*,26X,F10.3,2X,*LB PER BU*
          1)
      249  FORMAT(* *,25X,*GRAIN FLOW RATE OUT*,31X,F10.1,2X,*LB PER HR*)
           GO TO 111
      130  PRINT 131
      131  FORMAT (* *,*ERROR IN DATA CARDS*)
      140  CONTINUE
      141  END
```

Corn Run of 2/22/77

RUN NUMBER 3.

TDB AMBIENT	58.0	DEGREES F
ABS HUMIDITY IN	.00700	LB PER LB
AIRFLOW IN CONCURRENT FLOW AMBIENT	135.0	CFM
AMBIENT AIR DENSITY	13.70	CUBIC FT PER LB
HEATED AIR TEMP	400.0	DEGREES F
ABS HUMIDITY CONCURRENT FLOW EXHAUST	.07500	LB PER LB
AIRFLOW IN COUNTERFLOW	21.00	CFM
ABS HUMIDITY COUNTERFLOW EXHAUST	.03900	LB PER LB
GRAIN FLOW OUT	5.060	LB PER MIN
MOISTURE CONTENT WB IN	.2377	DECIMAL
MOISTURE CONTENT WB OUT	.1551	DECIMAL
GRAIN TEMPERATURE IN	42.0	DEGREES F
GRAIN TEMPERATURE OUT	64.0	DEGREES F
TEST WGT OUT	50.0	LBS PER BU
WGT OF WATER REMOVED FROM GRAIN	32.90	LB PER HR
WATER REMOVED IN CONCURRENT SECTION BY AIR	35.97	LB PER HR
TOTAL WATER REMOVED BY AIR	39.06	LB PER HR
AIRFLOW IN CONCURRENT SECTION	501.2	LB PER HR
AIRFLOW IN COUNTER CURRENT SECTION	92.0	LB PER HR
GRAIN FLOW RATE OUT	6.07	BU PER HR
GRAIN FLOW RATE OUT	303.6	LB PER HR
ENERGY CHANGE DUE TO TEMP AND MC IN AND OUT	1550.9	BTU PER HR
NET ENERGY INTO SYSTEM	46901.2	BTU PER HR
GROSS ENERGY INTO SYSTEM	50551.1	BTU PER HR
PROPANE BURNED	2.600	LB PER HR
ENERGY USED TO REMOVE WATER FROM GRAIN.	1439.2	BTU PER LB
WATER REMOVED FROM GRAIN	5.418	LB PER BU

Corn Run of 2/7/77

RUN NUMBER 1.

TDB AMBIENT	69.2	DEGREES F
ABS HUMIDITY IN	.00500	LB PER LB
AIRFLOW IN CONCURRENT FLOW AMBIENT	145.5	CFM
AMBIENT AIR DENSITY	13.43	CUBIC FT PER LB
HEATED AIR TEMP	400.0	DEGREES F
ABS HUMIDITY CONCURRENT FLOW EXHAUST	.07150	LB PER LB
AIRFLOW IN COUNTERFLOW	18.00	CFM
ABS HUMIDITY COUNTERFLOW EXHAUST	.04600	LB PER LB
GRAIN FLOW OUT	6.837	LB PER MIN
MOISTURE CONTENT WB IN	.2675	DECIMAL
MOISTURE CONTENT WB OUT	.1840	DECIMAL
GRAIN TEMPERATURE IN	50.0	DEGREES F
GRAIN TEMPERATURE OUT	69.0	DEGREES F
TEST WGT OUT	48.0	LBS PER BU
WGT OF WATER REMOVED FROM GRAIN	46.76	LB PER HR
WATER REMOVED IN CONCURRENT SECTION BY AIR	35.72	LB PER HR
TOTAL WATER REMOVED BY AIR	42.02	LB PER HR
AIRFLOW IN CONCURRENT SECTION	650.0	LB PER HR
AIRFLOW IN COUNTER CURRENT SECTION	80.4	LB PER HR
GRAIN FLOW RATE OUT	8.55	BU PER HR
GRAIN FLOW RATE OUT	410.2	LB PER HR
ENERGY CHANGE DUE TO TEMP AND MC IN AND OUT	1140.3	BTU PER HR
NET ENERGY INTO SYSTEM	52617.7	BTU PER HR
GROSS ENERGY INTO SYSTEM	53758.1	BTU PER HR
PROPANE BURNED	2.765	LB PER HR
ENERGY USED TO REMOVE WATER FROM GRAIN	1125.2	BTU PER LB
WATER REMOVED FROM GRAIN	5.472	LB PER BU

First Run - First Pass Soybeans

RUN NUMBER	1.	
TDB AMBIENT	68.0	DEGREES F
ABS HUMIDITY IN	.00300	LB PER LB
AIRFLOW IN CONCURRENT FLOW AMBIENT	128.0	CFM
AMBIENT AIR DENSITY	13.40	CUBIC FT PER LB
HEATED AIR TEMP	350.0	DEGREES F
ABS HUMIDITY CONCURRENT FLOW EXHAUST	.06750	LB PER LB
GRAIN FLOW OUT	9.800	LB PER MIN
MOISTURE CONTENT WB IN	.1360	DECIMAL
MOISTURE CONTENT WB OUT	.1140	DECIMAL
GRAIN TEMPERATURE IN	63.0	DEGREES F
GRAIN TEMPERATURE OUT	100.0	DEGREES F
TEST WGT OUT	57.0	LBS PER BU
WGT OF WATER REMOVED FROM GRAIN	14.97	LB PER HR
TOTAL WATER REMOVED BY AIR	33.58	LB PER HR
AIRFLOW IN CONCURRENT SECTION	573.1	LB PER HR
GRAIN FLOW RATE OUT	10.32	BU PER HR
GRAIN FLOW RATE OUT	588.0	LB PER HR
ENERGY CHANGE DUE TO TEMP AND MC IN AND OUT	8592.4	BTU PER HR
NET ENERGY INTO SYSTEM	31813.6	BTU PER HR
GROSS ENERGY INTO SYSTEM	40406.0	BTU PER HR
PROPANE BURNED	2.078	LB PER HR
ENERGY USED TO REMOVE WATER FROM GRAIN	2124.8	BTU PER LB
WATER REMOVED FROM GRAIN	1.451	LB PER BU

First Run - Second Pass Soybeans

RUN NUMBER	2.	
TDB AMBIENT	68.0	DEGREES F
ABS HUMIDITY IN	.00300	LB PER LB
AIRFLOW IN CONCURRENT FLOW AMBIENT	123.0	CFM
AMBIENT AIR DENSITY	13.40	CUBIC FT PER LB
HEATED AIR TEMP	300.0	DEGREES F
ABS HUMIDITY CONCURRENT FLOW EXHAUST	.05800	LB PER LB
GRAIN FLOW OUT	9.800	LB PER MIN
MOISTURE CONTENT WB IN	.1140	DECIMAL
MOISTURE CONTENT WB OUT	.0925	DECIMAL
GRAIN TEMPERATURE IN	100.0	DEGREES F
GRAIN TEMPERATURE OUT	95.0	DEGREES F
TEST WGT OUT	57.0	LBS PER BU
WGT OF WATER REMOVED FROM GRAIN	14.27	LB PER HR
TOTAL WATER REMOVED BY AIR	27.61	LB PER HR
AIRFLOW IN CONCURRENT SECTION	550.7	LB PER HR
GRAIN FLOW RATE OUT	10.32	BU PER HR
GRAIN FLOW RATE OUT	588.0	LB PER HR
ENERGY CHANGE DUE TO TEMP AND MC IN AND OUT	-2974.1	BTU PER HR
NET ENERGY INTO SYSTEM	34917.4	BTU PER HR
GROSS ENERGY INTO SYSTEM	31943.3	BTU PER HR
PROPANE BURNED	1.643	LB PER HR
ENERGY USED TO REMOVE WATER FROM GRAIN	2447.1	BTU PER LB
WATER REMOVED FROM GRAIN	1.383	LB PER BU

Second Run Soybeans

RUN NUMBER	3.	
TDB AMBIENT	74.0	DEGREES F
ABS HUMIDITY IN	.00630	LB PER LB
AIRFLOW IN CONCURRENT FLOW AMBIENT	141.0	CFM
AMBIENT AIR DENSITY	13.60	CUBIC FT PER LB
HEATED AIR TEMP	450.0	DEGREES F
ABS HUMIDITY CONCURRENT FLOW EXHAUST	.06800	LB PER LB
AIRFLOW IN COUNTERFLOW	15.00	CFM
ABS HUMIDITY COUNTERFLOW EXHAUST	.03150	LB PER LB
GRAIN FLOW OUT	11.004	LB PER MIN
MOISTURE CONTENT WB IN	.1247	DECIMAL
MOISTURE CONTENT WB OUT	.1057	DECIMAL
GRAIN TEMPERATURE IN	59.8	DEGREES F
GRAIN TEMPERATURE OUT	94.0	DEGREES F

TEST WGT OUT	58.2	LBS PER BU
WGT OF WATER REMOVED FROM GRAIN	14.33	LB PER HR
WATER REMOVED IN CONCURRENT SECTION BY AIR	33.48	LB PER HR
TOTAL WATER REMOVED BY AIR	35.20	LB PER HR
AIRFLOW IN CONCURRENT SECTION	622.1	LB PER HR
AIRFLOW IN COUNTER CURRENT SECTION	68.4	LB PER HR
GRAIN FLOW RATE OUT	11.35	BU PER HR
GRAIN FLOW RATE OUT	650.2	LB PER HR
ENERGY CHANGE DUE TO TEMP AND MC IN AND OUT	8920.3	BTU PER HR
NET ENERGY INTO SYSTEM	49553.3	BTU PER HR
GROSS ENERGY INTO SYSTEM	58473.5	BTU PER HR
PROPANE BURNED	3.007	LB PER HR
ENERGY USED TO REMOVE WATER FROM GRAIN	3457.6	BTU PER LB
WATER REMOVED FROM GRAIN	1.263	LB PER BU

APPENDIX B

CHEMICAL OIL ANALYSIS PROCEDURES

SAMPLING AND ANALYSIS OF COMMERCIAL FATS AND OILS

A.O.C.S. Official Method Ca 5a-40

Revised 1971
Corrected 1972

Free Fatty Acids

Definition: This method determines the free fatty acids existing in the sample.

Scope: Applicable to crude and refined vegetable and marine oils and animal fats.

A. Apparatus:

1. Oil sample bottles, 115 or 230 ml. (4 or 8 oz.) or 250-ml Erlenmeyer flasks.

B. Reagents:

1. Ethyl alcohol, 95% (U.S.S.D. Formulas 30 and 3A are permitted). The alcohol must give a definite, distinct and sharp end-point with phenolphthalein and must be neutralized with alkali to a faint but permanent pink color just before using.
2. Phenolphthalein indicator soln., 1% in 95% alcohol (see Note 1).
3. Sodium hydroxide solns., accurately standardized.

C. Procedure:

F. F. A. Range, %	Grams of Sample	Ml. of Alcohol	Strength of Alkali
0.00 to 0.2	56.4 ± 0.2	50	0.1 *N*
0.2 to 1.0	28.2 ± 0.2	50	0.1 *N*
1.0 to 30.0	7.05 ± 0.05	75	0.25 *N*
30.0 to 50.0	7.05 ± 0.05	100	0.25 or 1.0 *N*
50.0 to 100	3.525 ± 0.001	100	1.0 *N*

1. Samples must be well mixed and entirely liquid before weighing.
2. Use the table above to determine quantities to be used with various ranges of fatty acids. Weigh the designated size of sample into an oil-sample bottle or Erlenmeyer flask (see Note 2).
3. Add the specified amount of hot, neutralized alcohol and 2 ml. of indicator.
4. Titrate with alkali shaking vigorously to the appearance of the first permanent pink color of the same intensity as that of the neutralized alcohol before addition of the sample. The color must persist for 30 seconds.

D. Calculations:

1. The percentage of free fatty acids in most types of fats and oils is calculated as oleic acid, although in coconut and palm kernel oils it is frequently expressed as lauric acid and in palm oil in terms of palmitic acid.

   a. Free fatty acids as oleic, % =
   $$\frac{\text{Ml. of alkali} \times N \times 28.2}{\text{Weight of sample}}$$

   b. Free fatty acids as lauric, % =
   $$\frac{\text{Ml. of alkali} \times N \times 20.0}{\text{Weight of sample}}$$

c. Free fatty acids as palmitic, % =

$$\frac{\text{Ml. of alkali} \times N \times 25.6}{\text{Weight of sample}}$$

2. The free fatty acids are frequently expressed in terms of acid value instead of % free fatty acids. The acid value is defined as the number of mg. of KOH necessary to neutralize 1 g. of sample. To convert % free fatty acids (as oleic) to acid value, multiply the former by 1.99.

E. Notes:

1. Isopropanol, 99% may be used as an alternate solvent with crude and refined vegetable oils.
2. Cap bottle and shake vigorously for one minute if oil has been blanketed with carbon dioxide gas.

A.O.C.S. Official Method Cd 8-53
Official 1960

Peroxide Value

Definition: This method determines all substances, in terms of milli-equivalents of peroxide per 1000 grams of sample, which oxidize potassium iodide under the conditions of the test. These are generally assumed to be peroxides or other similar products of fat oxidation.

Scope: Applicable to all normal fats and oils including margarine. This method is highly empirical and any variation in procedure may result in variation in results.

A. Apparatus:

1. Pipet, Mohr, measuring type, 1-ml. capacity.
2. Erlenmeyer flasks, glass-stoppered, 250 ml.

B. Reagents:

1. Acetic acid-chloroform solution. Mix 3 parts by volume of glacial acetic acid, reagent grade, with 2 parts by volume of chloroform, U.S.P. grade.
2. Potassium iodide solution, saturated solution of KI, A.C.S. grade, in recently boiled distilled water. Make sure the solution remains saturated as indicated by the presence of undissolved crystals. Store in the dark. Test daily by adding 2 drops of starch solution to 0.5 ml. of the potassium iodide solution in 30 ml. of acetic acid-chloroform solution. If a blue color is formed which requires more than 1 drop of 0.1 *N* sodium thiosulfate solution to discharge, discard the iodide solution and prepare a fresh solution.
3. Sodium thiosulfate solution, 0.1 *N*, accurately standardized.
4. Sodium thiosulfate solution, 0.01 *N*, accurately standardized. This solution may be prepared by accurately pipetting 100 ml. of the 0.1 *N* solution into a 1000-ml. volumetric flask and diluting to volume with recently boiled distilled water.
5. Starch indicator solution, 1.0% of soluble starch in distilled water.

C. Procedure for Fats and Oils:

1. Weigh 5.00 ± 0.05 g. of sample into a 250-ml. glass-stoppered Erlenmeyer flask and then add 30 ml. of the acetic acid-chloroform solution. Swirl the flask until the sample is dissolved in the solution. Add 0.5 ml of saturated potassium iodide preferably using Mohr type measuring pipet.
2. Allow the solution to stand with occasional shaking for exactly 1 minute and then add 30 ml. of distilled water.
3. Titrate with 0.1 *N* sodium thiosulfate adding it gradually and with constant and vigorous shaking. Continue the titration until the yellow color has almost disappeared. Add ca. 0.5 ml. of starch indicator solution. Continue the titration, shaking the flask vigorously near the endpoint to liberate all the iodine from the chloroform layer. Add the thiosulfate dropwise until the blue color has just disappeared.

   Note: If the titration is less than 0.5 ml., repeat the determination using 0.01 *N* sodium thiosulfate solution.

Peroxide Value — Cd 8-53

4. Conduct a blank determination of the reagents daily. The blank titration must not exceed 0.1 ml. of the 0.1 *N* sodium thiosulfate solution.

D. Calculation:

1. Peroxide value as milliequivalents of peroxide per 1000 g. of sample =

$$\frac{(S-B)(N)\ (1000)}{\text{weight of sample}}$$

B = Titration of blank

S = Titration of sample.

N = Normality of sodium thiosulfate solution.

E. Procedure for Margarine:

1. Proceed as directed above in Paragraphs 1 through 4 after preparation of the sample as directed below.
2. Melt sample by heating with constant stirring on hot plate set at low heat, or by heating in air oven at 60–70°C. Avoid excessive heating and particularly prolonged exposure of oil to temperatures above 40°C.
3. When completely melted, remove the sample from the hot plate or oven and allow to settle in a warm place until the aqueous portion and most of the milk solids have settled to the bottom.
4. Decant the oil into a clean beaker and filter through a Whatman No. 4 paper (or equivalent) into another clean beaker. Do not reheat unless absolutely necessary for filtration. The sample should be clear and brilliant.

CRUDE FAT DETERMINATION OF SOYBEAN SAMPLES

(Official Methods of Analysis of the Association of Official Agri. Chemists)

The whole batch (about 1.0 lb) of soybean was ground in a Wiley Mill for 5.0 min. The ground sample was dried in a vacuum oven (v.o.) at 100°C and 29 inches pressure for 5.0 hours. It was then cooled in a desiccator.

About 2.0 grams of V.O. dried sample was weighed accurately with a microbalance and soxhlet extracted with anhydrous ethyl ether for 12.0 hrs., and the yield of crude fat extract was determined as percent. In all trials duplicates were used.

(Written by S. Dokhani)

APPENDIX C

COMPUTER SIMULATIONS

Second Run Conditions

Soybean Drying Simulation

CONCURRENT GRAIN DRYER SIMULATION
USING THE SABBAH THINLAYER EQUATION FOR BEANS

INPUT CONDITIONS:
NUMBER OF STAGES TO BE SIMULATED 1
AMBIENT TEMP, F74.
INLET MOISTURE CONTENT, WET BASIS PERCENT12.47

STAGE 1 INPUT CONDITIONS:
INLET AIR TEMP, F450.
INLET ABS HUM RATIO.0063
AIRFLOW RATE, CFM/SQ FT(AT AMBIENT CONDITIONS) 141.
GRAIN FLOW RATE, BU/HR/SQ FT 11.38
DRYER LENGTH, FT 3.
OUTPUT INTERVAL, FT.1

PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0003
AIRFLOW RATE, LB DRY AIR/HR/SQ FT 605.7 CFM AT TIN 240.3
HEAT TRANSFER COEF, BTU/HR/SQ FT/F 15.902
EQUIL MC, WB PERCENT .04 DRY BASIS, DECIMAL .0004
INLET MC, DRY BASIS DECIMAL .1425
GRAIN VELOCITY, FT/HR 14.16 LB DRY MATTER/HR/SQ FT 572.21

DEPTH FT	TIME HR	AIR TEMP F	ABS HUM LB/LB	REL HUM DECIMAL	GRAIN TEMP F	MC WB PERCENT	MC DB DECIMAL
.00	.00	443.9	.0063	.0004	77.0	12.47	.1425
.10	.01	219.0	.0073	.0098	184.3	12.39	.1415
.20	.01	194.2	.0089	.0190	191.9	12.26	.1397
.30	.02	192.2	.0105	.0242	190.5	12.13	.1380
.41	.03	189.6	.0121	.0294	188.2	12.00	.1364
.56	.04	186.6	.0141	.0365	185.3	11.83	.1342
.62	.04	185.3	.0149	.0398	184.1	11.76	.1333
.72	.05	183.5	.0161	.0446	182.3	11.66	.1320
.82	.06	181.7	.0173	.0495	180.7	11.57	.1308
.98	.07	179.1	.0191	.0578	178.1	11.42	.1290
1.05	.07	178.1	.0197	.0611	177.1	11.37	.1283
1.11	.08	177.1	.0204	.0644	176.2	11.31	.1276
1.24	.09	175.2	.0216	.0710	174.4	11.21	.1263
1.31	.09	174.4	.0222	.0743	173.5	11.16	.1257
1.47	.10	172.3	.0235	.0826	171.5	11.05	.1242
1.54	.11	171.5	.0241	.0859	170.7	11.01	.1237
1.60	.11	170.7	.0246	.0892	170.0	10.96	.1231
1.73	.12	169.2	.0255	.0958	168.5	10.88	.1221
1.80	.13	168.5	.0260	.0991	167.8	10.84	.1216
1.93	.14	167.2	.0269	.1056	166.5	10.77	.1207
2.06	.15	165.9	.0277	.1120	165.3	10.70	.1198
2.13	.15	165.3	.0281	.1152	164.7	10.66	.1194
2.26	.16	164.1	.0289	.1216	163.5	10.60	.1185
2.32	.16	163.5	.0293	.1248	163.0	10.57	.1181
2.46	.17	162.4	.0300	.1310	161.9	10.50	.1174
2.55	.18	161.6	.0305	.1357	161.1	10.46	.1168
2.62	.19	161.1	.0309	.1388	160.6	10.43	.1165
2.75	.19	160.1	.0315	.1449	159.7	10.38	.1158
2.82	.20	159.7	.0318	.1479	159.2	10.35	.1155
2.95	.21	158.8	.0324	.1539	158.3	10.30	.1148
3.01	.21	158.3	.0327	.1569	157.9	10.28	.1145

STATIC PRESSURE, INCHES OF H2O 9.08
HORSEPOWER/SQ FT .20

First Run Conditions

Soybean Drying Simulation

ENERGY INPUTS, BTU/BU
FAN (.5 EFF) 90.
HEAT AIR 4900.
MOVE GRAIN 0.
TOTAL 4990.

WATER REMOVED, LB/BU 1.40

BTU/LB H2O 3552.21

QUALITY CHANGE, PERCENT 11.18

QUALITY CHANGE, PERCENT 11.18

ESTIMATE OF THE MOISTURE REMOVAL TO COOL TO AMBIENT
MOISTURE REMOVED, POINTS WET BASIS 2.13
FINAL MOISTURE CONTENT, WET BASIS 8.49

TOTAL BTU/LB H2O 3552.21
END CONCUR
1.004 CP SECONDS EXECUTION TIME

READY 16.33.51

zzzzlgo.
EXEC BEGUN.16.34.06.
CONCURRENT GRAIN DRYER SIMULATION
USING THE SABBAH THINLAYER EQUATION FOR BEANS

INPUT CONDITIONS:
NUMBER OF STAGES TO BE SIMULATED 2
AMBIENT TEMP, F68.
INLET MOISTURE CONTENT, WET BASIS PERCENT13.6

STAGE 1 INPUT CONDITIONS:
INLET AIR TEMP, F350.
INLET ABS HUM RATIO.003
AIRFLOW RATE, CFM/SQ FT(AT AMBIENT CONDITIONS) 128.
GRAIN FLOW RATE, BU/HR/SQ FT 10.32
DRYER LENGTH, FT 3.
OUTPUT INTERVAL, FT.1
TEMPERING LENGTH, FT 5.

PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0005
AIRFLOW RATE, LB DRY AIR/HR/SQ FT 559.1 CFM AT TIN 196.4
HEAT TRANSFER COEF, BTU/HR/SQ FT/F 15.167
EQUIL MC, WB PERCENT .05 DRY BASIS, DECIMAL .0005
INLET MC, DRY BASIS DECIMAL .1574
GRAIN VELOCITY, FT/HR 12.84 LB DRY MATTER/HR/SQ FT 518.92

DEPTH FT	TIME HR	AIR TEMP F	ABS HUM LB/LB	REL HUM DECIMAL	GRAIN TEMP F	MC WB PERCENT	MC DB DECIMAL
.00	.00	347.6	.0030	.0005	69.2	13.60	.1574
.10	.01	173.7	.0038	.0132	150.8	13.54	.1566
.20	.02	158.6	.0049	.0243	155.7	13.45	.1554
.34	.03	155.1	.0064	.0347	154.1	13.32	.1537
.41	.03	154.1	.0071	.0393	153.1	13.27	.1530
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]	.05	151.2	.0090	.0533	150.4	13.11	.1509
[illegible]	.05	149.9	.0099	.0604	149.1	13.04	.1500
.76	.07	146.7	.0120	.0794	146.0	12.87	.1477
1.03	.08	146.0	.0125	.0841	145.3	12.83	.1471
1.09	.09	[illegible]	.0130	[illegible]	144.6	12.79	.1466
1.16	.09	144.6	.0135	[illegible]	143.9	12.75	.1461
1.22	.10	143.9	.0140	[illegible]	[illegible]	12.71	[illegible]
1.35	.11	142.6	.0148	.1079	142.0	12.64	[illegible]
1.42	.11	[illegible]	.0152	.1126	141.4	12.60	.1442
[illegible]	.12	[illegible]	.0162	.1244	140.0	12.52	.1431
[illegible]	.13	[illegible]	.0166	[illegible]	139.4	12.49	[illegible]
[illegible]	.13	[illegible]	.0170	[illegible]	138.9	12.46	[illegible]
[illegible]	.14	[illegible]	[illegible]	[illegible]	[illegible]	12.40	.1416
[illegible]	.15	[illegible]	.0180	[illegible]	137.3	[illegible]	.1412
2.04	.16	[illegible]	.0187	[illegible]	136.4	12.32	.1405
2.11	.16	[illegible]	.0190	.1614	135.9	12.29	.1402
[illegible]	.17	[illegible]	.0196	.1704	135.0	12.24	.1395
[illegible]	[illegible]	[illegible]	[illegible]	.1749	134.6	12.22	.1392
[illegible]	[illegible]	[illegible]	.0205	[illegible]	133.8	12.17	[illegible]
[illegible]	.19	[illegible]	.0208	[illegible]	[illegible]	12.15	.1383
[illegible]	[illegible]	[illegible]	[illegible]	.1970	132.4	12.09	.1376
[illegible]	.21	[illegible]	.0217	.2033	132.0	12.07	.1373
[illegible]	[illegible]	[illegible]	.0222	.2118	131.3	12.03	[illegible]
[illegible]	[illegible]	[illegible]	.0224	.2159	131.0	12.01	[illegible]
3.0[illegible]	.24	[illegible]	.0229	.2242	130.3	11.97	[illegible]

[illegible], INCHES OF H2O 7.71
[illegible]

[illegible]
[illegible] 77.
[illegible] 3713.
[illegible] GRAIN 3.
TOTAL 3793.

WATER REMOVED, LB/BU 1.08

BTU/LB H2O [illegible]

[illegible] 7.69

[illegible] CONDITIONS:
[illegible]
[illegible].003
[illegible] AMBIENT CONDITIONS) 125.
[illegible] 10.32
[illegible]
[illegible]

[illegible] VALUES

[illegible] DECIMAL [illegible]
[illegible] CFM AT TIN 177.1
[illegible] 14.015
[illegible] .09 DRY BASIS, DECIMAL .0009
[illegible] DECIMAL [illegible]
[illegible] 12.34 LB DRY MATTER/HR/SQ FT 518.92

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC DB
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	DECIMAL

.10	.01	182.9	.0041	.0095	179.1	11.88	.1348
.20	.02	183.2	.0055	.0156	180.9	11.77	.1334
.32	.02	180.3	.0070	.0211	179.1	11.65	.1319
.41	.03	178.4	.0082	.0257	177.4	11.55	.1306
.51	.04	176.7	.0093	.0303	175.7	11.46	.1295
.61	.05	175.1	.0104	.0350	174.1	11.37	.1283
.71	.06	173.6	.0114	.0397	172.7	11.29	.1273
.81	.06	172.1	.0124	.0444	171.3	11.21	.1263
.97	.08	169.8	.0139	.0524	169.1	11.09	.1247
1.04	.08	169.0	.0145	.0556	168.2	11.04	.1241
1.10	.09	168.2	.0150	.0588	167.4	11.00	.1236
1.23	.10	166.6	.0161	.0651	165.9	10.91	.1225
1.36	.11	165.1	.0171	.0715	164.4	10.83	.1214
1.43	.11	164.4	.0176	.0747	163.7	10.79	.1210
1.57	.12	162.7	.0187	.0826	162.1	10.70	.1198
1.66	.13	162.0	.0191	.0857	161.4	10.66	.1193
1.72	.13	161.4	.0195	.0889	160.8	10.63	.1189
1.85	.14	160.2	.0203	.0951	159.6	10.56	.1181
1.92	.15	159.6	.0207	.0982	159.1	10.53	.1177
2.05	.16	158.5	.0215	.1044	158.0	10.47	.1169
2.12	.16	157.9	.0218	.1075	157.4	10.44	.1165
2.25	.18	156.9	.0225	.1135	156.4	10.38	.1158
2.31	.18	156.4	.0228	.1166	155.9	10.35	.1155
2.45	.19	155.4	.0235	.1225	155.0	10.30	.1148
2.54	.20	154.7	.0239	.1270	154.3	10.26	.1143
2.61	.20	154.3	.0242	.1299	153.8	10.24	.1140
2.73	.21	153.4	.0248	.1358	153.0	10.19	.1134
2.81	.22	153.0	.0251	.1386	152.6	10.17	.1132
2.94	.23	152.2	.0256	.1443	151.8	10.12	.1126
3.00	.23	151.8	.0259	.1472	151.4	10.10	.1123

STATIC PRESSURE, INCHES OF H2O 7.47
HORSEPOWER/SQ FT .14

ENERGY INPUTS, BTU/BU
FAN (.5 EFF) 71.
HEAT AIR 2937.
MOVE GRAIN 0.
TOTAL 3010.

WATER REMOVED, LB/BU 1.17

BTU/LB H2O 2557.22

QUALITY CHANGE, PERCENT 12.39

QUALITY CHANGE, PERCENT 20.03

ESTIMATE OF THE MOISTURE REMOVAL TO COOL TO AMBIENT
MOISTURE REMOVED, POINTS WET BASIS 2.04
FINAL MOISTURE CONTENT, WET BASIS 8.38

TOTAL BTU/LB H2O 3002.96
END CONCUR
2.014 CP SECONDS EXECUTION TIME

READY 16.47.45

LOGOUT,T.

JOB COST: $ 2.07

Second Run Conditions

Corn Drying Simulation

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[illegible]
[illegible].15.56.19.
[illegible] GRAIN DRYER SIMULATION
USING THE [illegible] THINLAYER EQUATION FOR CORN

INPUT CONDITIONS:

     INLET AIR TEMP, F430.
     INLET ABS HUM RATIO.0063
     AIRFLOW RATE, CFM/SQ FT(AT AMBIENT CONDITIONS) 141.
     AMBIENT TEMP, F74.
     INLET GRAIN TEMP, F70.
     INLET MOISTURE CONTENT, WET BASIS PERCENT12.47
     GRAIN FLOW RATE, BU/HR/SQ FT 11.38
     DRYER LENGTH, FT 3.
     OUTPUT INTERVAL, FT.1

PRELIMINARY CALCULATED VALUES

REL HUM, DECIMAL .0003  AIRFLOW RATE, LB DRY AIR/HR/SQ FT 605.7  CFM AT TIN 240
3
HEAT TRANSFER COEF, BTU/HR/SQ FT/F  15.902
EQUIL MC, WB PERCENT   .13   DRY BASIS, DECIMAL .0013
INLET MC, DRY BASIS DECIMAL .1425
GRAIN VELOCITY, FT/HR 14.16 LB DRY MATTER/HR/SQ FT  548.01
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DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC DB
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	DECIMAL
.00	.00	447.5	.0063	.0003	71.6	12.47	.1425
.10	.01	222.6	.0073	.0091	217.2	12.39	.1414
.21	.01	217.9	.0084	.0116	217.1	12.29	.1401
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

.41	.03	21[illegible].1	.0106	.0156	21[illegible].4	12.11	.1377
.53	.04	212.1	.0117	.0180	211.4	12.01	.1364
.61	.04	210.7	.0126	.0198	210.0	11.94	.1356
.71	.05	209.0	.0135	.0219	208.5	11.86	.1345
.80	.06	[illegible].4	.0144	.0242	206.8	11.78	.1335
.90	.06	205.3	.0153	.0264	205.2	11.70	.1325
1.00	.07	204.3	.0162	.0288	203.7	11.63	.1316
1.13	.08	[illegible]	.0173	.0320	201.7	11.53	.1303
1.23	.09	200.9	.0181	.0344	200.3	11.16	.1295
1.31	.09	199.7	.0187	.0365	199.1	11.41	.1287
1.41	.10	198.3	.0195	.0390	197.8	11.34	.1279
1.51	.10	197.0	.0202	.0416	196.5	11.28	.1271
1.61	.11	195.7	.0209	.0442	195.2	11.21	.1263
1.71	.12	194.4	.0216	.0468	193.9	11.15	.1255
1.80	.13	193.2	.0223	.0495	192.7	11.10	.1248
1.90	.13	192.0	.0229	.0521	171.5	11.04	.1241
2.05	.14	190.3	.0237	.0562	189.8	10.96	.1231
2.11	.15	189.6	.0243	.0580	189.1	10.92	.1226
2.21	.15	188.5	.0248	.0608	188.0	10.87	.1220
2.[illegible]	.16	187.4	.0254	.0635	187.0	10.82	.1213
2.41	.17	186.4	.0260	.0663	186.0	10.77	.1207
2.51	.18	185.4	.0265	.0691	185.0	10.73	.1202
2.61	.18	184.4	.0270	.0719	184.0	10.68	.1196
2.70	.19	183.5	.0275	.0747	183.1	10.64	.1190
2.80	.20	182.6	.0280	.0774	182.2	10.60	.1185
2.90	.20	181.7	.0284	.0802	181.3	10.55	.1180
3.02	.21	180.7	.0290	.0835	180.3	10.51	.1174

First Run -
First Pass
Conditions

Corn Drying
Simulation

```
STATIC PRESSURE, INCHES OF H2O 15.79
[illegible] .05

ENERGY IN BTUS, BTU/LB
        FAN (.5 EFF)    157.
        HEAT AIR       4900.
        MOVE GRAIN        0.
        TOTAL          5057.

WATER REMOVED, LB/BU   1.21

[illegible]
        END [illegible]
        1.293 CP SECONDS EXECUTION TIME

READY 16.02.46

[illegible].
 EXEC BEGUN.16.03.02.
CONCURRENT GRAIN DRYER SIMULATION
USING THE THOMPSON   THINLAYER EQUATION FOR CORN

INPUT CONDITIONS:

    INLET AIR TEMP, F350.
    INLET ABS HUM RATIO.003
    AIRFLOW RATE, CFM/SQ FT(AT AMBIENT CONDITIONS) 128.
    AMBIENT TEMP, F68.
    INLET GRAIN TEMP, F70.
    INLET MOISTURE CONTENT, WET BASIS PERCENT13.6
    GRAIN FLOW RATE, BU/HR/SQ FT 10.32
    DRYER LENGTH, FT 3.
    OUTPUT INTERVAL, FT.1

PRELIMINARY CALCULATED VALUES
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REL HUM, DECIMAL .0005 AIRFLOW RATE, LB DRY AIR/HR/SQ FT 559.1 CFM AT TIN 196
4
HEAT TRANSFER COEF, BTU/HR/SQ FT/F 15.167
EQUIL MC, WB PERCENT .18 DRY BASIS, DECIMAL .0018
INLET MC, DRY BASIS DECIMAL .1574
GRAIN VELOCITY, FT/HR 12.84 LB DRY MATTER/HR/SQ FT 496.96

DEPTH	TIME	AIR TEMP	ABS HUM	REL HUM	GRAIN TEMP	MC WB	MC DB
FT	HR	F	LB/LB	DECIMAL	F	PERCENT	DECIMAL
.00	.00	347.0	.0030	.0005	70.6	13.60	.1574
.10	.01	180.2	.0040	.0120	176.6	13.52	.1563
.20	.02	176.7	.0050	.0163	176.0	13.43	.1552
.31	.02	174.9	.0060	.0205	174.3	13.34	.1540
.41	.03	173.3	.0070	.0246	172.7	13.26	.1529
.52	.04	171.5	.0080	.0293	170.9	13.18	.1518
.62	.05	170.0	.0089	.0335	169.5	13.10	.1508
.72	.06	168.6	.0097	.0378	168.1	13.04	.1499
.82	.06	167.3	.0105	.0420	166.8	12.97	.1490
.93	.07	165.8	.0113	.0471	165.3	12.90	.1480
1.03	.08	164.5	.0120	.0514	164.1	12.83	.1472
1.13	.09	163.3	.0127	.0555	162.9	12.78	.1465
1.23	.10	162.2	.0134	.0602	161.3	12.72	.1458
1.32	.10	161.1	.0140	.0646	160.7	12.67	.1451
1.42	.11	160.1	.0146	.0689	159.7	12.62	.1444
1.52	.12	159.1	.0151	.0733	158.7	12.57	.1438
1.62	.13	158.1	.0157	.0776	157.7	12.52	.1431
1.70	.13	157.3	.0161	.0812	157.0	12.48	.1427
1.83	.14	156.2	.0168	.0869	155.8	12.43	.1419
1.93	.15	155.3	.0172	.0911	155.0	12.39	.1414
2.03	.16	154.5	.0177	.0953	154.2	12.35	.1409
2.13	.17	153.7	.0181	.0995	153.4	12.31	.1404
2.23	.17	153.0	.0186	.1034	152.7	12.27	.1399
2.32	.18	152.3	.0190	.1076	152.0	12.24	.1395
2.42	.19	151.6	.0194	.1116	151.3	12.21	.1390
2.52	.20	150.9	.0197	.1155	150.6	12.17	.1385
2.72	.21	149.7	.0203	.1226	149.5	12.12	.1379
2.77	.22	149.3	.0206	.1251	149.1	12.10	.1376
2.83	.22	149.0	.0208	.1276	148.7	12.08	.1374
2.93	.23	148.4	.0211	.1313	148.2	12.05	.1371
3.03	.24	147.8	.0214	.1350	147.6	12.03	.1367

STATIC PRESSURE, INCHES OF H2O 12.30
HORSEPOWER/SQ FT .23

ENERGY INPUTS, BTU/BU
FAN (.5 EFF) 122.
HEAT AIR 3718.
MC & GRAIN 0.
TOTAL 3840.

WATER REMOVED, LB/BU 1.09

BTU/LB H2O 3523.63
END CONCUR
1.239 CP SECONDS EXECUTION TIME

READY 16.09.37

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