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A simulation study of corn production and low-temperature drying for Central Iowa

Gary Richard Van Ee
Iowa State University

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A SIMULATION STUDY OF CORN PRODUCTION AND LOW-TEMPERATURE DRYING FOR CENTRAL IOWA

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A simulation study of corn production and low-temperature drying for Central Iowa

by

Gary Richard Van Ee

A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural Engineering

Approved:

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For the Graduate College Iowa State University, Ames, Iowa

1980
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LIST OF SYMBOLS AND DEFINITIONS

Ac Acres
ASAE American Society of Agricultural Engineers
bu Bushel
cfm Cubic Feet Per Minute
CPU Central Processing Unit
ft Feet
hr Hour
I/O Input and/or Output
kg Kilogram
kW Kilowatt
kWh Kilowatt-hour
lb pounds
m Meter
s Second
t Metric Ton
USDA United States Department of Agriculture
yr Year
°C Degrees Celsius
°F Degrees Fahrenheit
% MCWB Percent Moisture Content Wet Base
$ Dollars
INTRODUCTION

During the last decade, significant advances have been reported in the ability to simulate the planting, growing, harvesting, and conditioning segments of the agricultural production system. The systematic analysis necessary during conception and development of the models typically produces results in addition to the completed model. The modeling effort enhances the researcher's understanding of the simulated process and, second, it highlights the most crucial area that needs future research. Validation testing and sensitivity analysis of the model can lead to optimization of the specific process being simulated.

In view of agriculture's increasing dependence on nonrenewable resources, the existing agricultural models take on a new significance. No longer can we be satisfied with local optimization of specific processes. We must integrate our modeling technology into comprehensive global models that are sensitive to the complete management, machine, crop, weather, and soil interface of a typical agricultural production system. Hopefully, these efforts will make possible the development of management strategies and design recommendations that can improve the productivity and/or reduce the energy dependence of modern agriculture.

Due to the increased capacity of present digital computing systems and their improved cost efficiency, such comprehensive modeling is now practical. Similarly, the overall objective of this investigation was to conduct a comprehensive simulation study of corn production and low-temperature corn drying for Central Iowa conditions.
OUTLINE OF DISSERTATION FORMAT AND OBJECTIVES

This dissertation consists of three sections. Each section was written and distributed as a separate paper. The candidate (Gary R. Van Ee) conducted the research and authored the papers under the supervision and editing assistance of his research leader (Gerald L. Kline). Section I (CORNISIM—A Corn Production for Central Iowa) and Section II (FALDRY—A Model for Low-Temperature Corn Drying Systems) were formally presented in December at the 1979 Winter Meeting of the American Society of Agricultural Engineers held at the Hyatt-Regency Hotel in New Orleans, Louisiana. Section III (Management Strategies for Corn Production and Low-Temperature Drying) was presented six months earlier at the 1979 Joint Summer Meeting of the American Society of Agricultural Engineers and the Canadian Society of Agricultural Engineers held at the University of Manitoba in Winnipeg, Canada.

Section I reports on the development of a computer simulation model named CORNISIM. CORNISIM simulates a complete corn production enterprise. Given a specific management strategy, machinery capacity, and cropping season, CORNISIM simulates planting, crop development, yield, and harvesting. CORNISIM was developed to provide the simulated flow of harvested grain.

Section II reports on the development of a computer simulation model named FALDRY. FALDRY simulates a system of low-temperature corn drying

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1During the period of this research project both were employees of the United States Department of Agriculture and were functioning as collaborators with the Iowa State University Experiment Station.
bins. FALDRY inputs include bin specifications, weather data, and the incoming flow of harvested grain. FALDRY was developed to predict the success or failure of a low-temperature corn drying system and the amount of electrical energy it would consume.

Section III reports on a simulation study of corn production and low-temperature drying using the two computer models - CORNSIM and FALDRY. The study addressed three major objectives:

1. Determine the relative benefits of additional fan power versus the use of supplement heat to enhance the performance of a low-temperature drying system.

2. Test the feasibility of designing a low-temperature drying system to match the corn harvesting capacity of a typical Central Iowa farming enterprise.

3. Develop the optimum daily filling strategy and design recommendations for a low-temperature corn drying system for Central Iowa.
SECTION I:
CORNSim - A CORN PRODUCTION MODEL
FOR CENTRAL IOWA
INTRODUCTION

CORNSIM\textsuperscript{1} is a deterministic corn production model. It was developed to supply simulated harvested grain flow data for a corn drying and storage study. CORNSIM provides simulated grain flow data that are specific for a given cropping season, machinery capacity, and management strategy. Central Iowa data are used to determine the potential corn yields and available field days. Simulation is used to predict corn planting, physiological development, dry-down in the field, and harvesting operations.

\textsuperscript{1}CORNSIM is a user-oriented computer model. Both input and output (I/O) forms of CORNSIM are designed to be easily understood by researcher, designer, student, and farm manager alike. All I/O specifications of management strategy, machinery capacity, field operations, and harvested grain flow are expressed in their "common" English units, i.e., field size- acres, corn quantity- bushels (1 bu. = bushel of corn = 47.32 pounds of dry matter), grain temperature- \textdegree{}F. Thus it is imperative that this paper use "common" English units to enhance the reader's ability to understand and use the CORNSIM model.
LITERATURE REVIEW

Plant Models

Computer modeling of plant growth began in the mid-1960s. During the last 15 years, a large number of plant models have been developed and reported. They vary from generalized photosynthesis models to crop and location-specific models for grasses, feed grains, and fiber crops. There are basically two techniques used either exclusively or in combination to model a plant community.

The simplest is the regression equation method. Its range of application is limited to the conditions under which the equations were developed. It can be useful to predict the final plant size, weight, or grain yield, but not designed to simulate the daily internal functions of the plant. Norman (1979) gives a summary of this type of model.

The second technique is to model growth functions of the plant. These models can simulate photosynthesis, respiration, water and nutrient uptake by the roots, and evapotranspiration of plants on a daily basis. Canopy, stem, and root growth are predicted daily, based on the net accumulation of photosynthate. Duncan et al. (1967) were among the first to develop this type of model. These models are considerably more difficult to develop and use significantly more computer time to run than regression models, but they have several advantages:

1. In addition to predicting final yields, they have the ability to simulate the development of the entire plant.

2. The systematic analysis necessary in the development of the
model significantly enhances the modeler's understanding of the plant functions.

3. These models can sometimes be applied to soils, locations, and climatic conditions beyond those not used in the model development.

Growth simulation models for corn have been developed by Curry (1969), Curry and Chen (1969), Duncan (1975), and Childs et al. (1977). Fritten et al. (1976) reported on evaluation of the Duncan and Childs models under Pennsylvania conditions. The yield predictions of the Duncan model developed in Kentucky were more accurate than the predictions of the Childs model which was developed for drier Nebraska conditions. Both models predict phenological development by accumulating growth degree units (Newman et al., 1968) after planting. Both models need to be fine tuned to actual date of tasseling before accurate yield predictions can be obtained.

Most corn growth models do not simulate the dry-down stage of crop development. The Childs model accumulates growing-degree units through the grain filling period and terminates by predicting maturity. The Duncan model proceeds one step farther by assuming a fixed daily drying rate.

Bruns et al. (1975) reported on the development and verification of a corn dry-down simulation model for Indiana conditions. The model required mean daily observations for radiation, wind speed, dry bulb and dew-point temperature, and precipitation. The model adequately simulated the dry-down rate of the corn for the three test years.
Production System Models

There have been many efforts reported to model agricultural production systems. Modeling techniques commonly used include linear programming, network analysis, dynamic programming, inventory models, and simulation. The simulation method offers the most potential if you wish to model the combined effects of weather, management strategy, machinery capacity, and plant growth.

Morey et al. (1969) were among the first to report the development of a corn production simulator. Their model was designed to assist in the evaluation of corn harvesting, drying, and marketing systems for Indiana conditions. The model used the growing-degree method of Newman et al. (1968) to predict crop maturity. Fixed daily rates for field-drying and field losses were assumed. The model was admittedly crude, but it was useful for determining the relative effects of changing harvest capacity, drying rate, and management strategies.

Holtman et al. (1970) reported the development of a similar model for Michigan conditions. Their model was a more detailed simulation, but its scope was limited to the harvest phase. It began simulation on a user-specified date when corn reached physiological maturity (30% MCWB grain). Field drying was predicted using regression equations from Schmidt and Hallauer (1966) and recorded weather data.

Field trafficability was predicted based on a simulation of soil moisture using actual weather data. Harvesting performance was a function of machine size, lodging, yield, and man-machine performance coefficients. Simulation of several alternates for a user-specific situation could be
used in an effective way to develop decision-making information.

Ayres (1973) used a probabilistic method to simulate crop maturity, field dry-down, field trafficability and subsequent harvest operation for a corn forage harvesting system. He concluded that the model was an effective tool to predict relative field performances, reliabilities and costs of alternate machine systems.

A discrete event-oriented simulation model for corn was developed by Parsons and Holtman (1976). They enhanced the previously reported Michigan corn production model by adding event-oriented simulation of the machine systems using the GASP II language. By simulating the activity of each specific machine, the model could be used to determine realistic performance coefficients. Due to the large size and major computational requirement of the model, only a very limited number of actual runs were made.

Benock et al. (1977) reported the development of SQUASH (Simulation of Queues Involving Unloadings and Arrivals for Systems of Harvesting). The user has complete flexibility in describing a specific farm situation to include the performance of the harvesting, delivery, handling and drying equipment. The model simulates the activity of each piece of equipment and continuously reports its status and overall efficiency. The model is specifically designed to point out bottlenecks in the harvesting system. Optimum machinery systems for user-specific situations can effectively be developed by making repeated SQUASH simulations.
The local data base of weather, crop progress, and field conditions necessary to develop and validate the crop model for central Iowa was available and amazingly complete. The information and its sources are as follows:


2. Actual yields of long, medium, and short season corn varieties under top technology production methods reported by Iowa Crop Improvement Association (1958-1975).

3. The 5-year averages of the effects of planting dates on the yields of long, medium, and short season corn as reported by Pioneer Seed Company (1974; 1975).

4. The 5-year averages of the effects of harvest dates on field loss as reported by Pioneer Seed Company (1974; 1975).

5. Eight seasons of corn dry-down data as observed by Schmidt (1968a) were available in USDA files at Iowa State University.

6. A complete record of observed "available field days" for the central Iowa area as reported by the Iowa Crop and Livestock Reporting Service (1958-1975).

7. A complete record of the planting, physiological development, and harvesting of the central Iowa corn crop as reported by Iowa Crop and Livestock Reporting Service (1958-1975).
DEVELOPMENT OF CORNSIM

General Outline

CORNSIM increments on a 24-hour time base. It uses 18 data sets including date code, daily average weather conditions, field trafficability code, and cumulative growing degrees (Newman Method) for years 1958-1975. Operating within the limitations of the given management strategy, machine capacity, and soil conditions, the model simulates the progression of the planting operation. Once the individual fields are planted, the plant growth stage (sprouting to flowering phase) is simulated by accumulating growing degree units. Next, the ear development stage (flowering to 75% kernel moisture) is simulated by accumulating calendar days. Third, the maturing and dry-down stage (75% kernel moisture to harvest) is simulated using a five-stage regression algorithm. Each of the five equations operates within a limited moisture range. The rate of field drying is a function of dry bulb temperature, wet bulb depression, and/or equilibrium moisture content of the grain. Finally, subject to the given limitations of machine capacity, management strategy, field trafficability, and weather, the harvesting operation is simulated concurrent with the latter part of the maturing and dry-down stage. The simulated harvested grain flow data produced by the model consist of year, Julian date, grain quantity, grain moisture, and grain temperature. Figure 1 is a flowchart of CORNSIM.
CORNSIM

INPUTS:
CROP
ACREAGE
MACHINE
CAPACITY
MANAGEMENT
STRATEGY

PLANTING

AVAILABLE
FIELD DAYS
MAXIMUM YIELD
POTENTIAL
GROW DEGREE
UNITS

EARLY
GROWTH

EAR
DEVELOPMENT

75% MCWB
TO
37% MCWB

37% MCWB
TO
20% MCWB

20% MCWB
TO
EQUILIBRIUM

HARVEST

OUTPUT

DATA FILE:
WEATHER
SOIL
PLANT

NUMBER OF
DEVELOPMENT DAYS

DRY BULB TEMP.
FIRST FREEZE

WET BULB DEPRESSION
FIRST FREEZE, AND
EQUILIBRIUM GRAIN
MOISTURE

EQUILIBRIUM GRAIN
MOISTURE

DRY BULB TEMPERATURE AND
AVAILABLE FIELD DAYS

SIMULATED HARVESTED GRAIN FLOW DATA
YEAR, DAY, QUANTITY, MOISTURE, AND TEMPERATURE

Figure 1. Flowchart of CORNSIM
Simulation of Planting

CORN SIM begins simulation on April first (Julian Date 91) for each production season and terminates simulation on December 31. The winter months of January, February, and March are not included in simulation. The field trafficability data set contains a "go" or "no go" value for all 275 days of the cropping season. There are two management inputs that determine when planting starts. First, the user specifies the minimum number of spring "go" days needed for primary tillage before planting can begin. Second, the user defines the earliest allowable date for planting to begin. When both of these requirements are met, the planting operation begins. Planting can only proceed on "go" days at a rate consistent with the user-supplied planter capacity and work-time strategy. CORNSIM is capable of planting a maximum of 30 "fields" of corn. The physiological development of each field is individually simulated through the rest of the season.

Predicting Potential Yield

Due to the availability of corn yield data from the research plots of the Iowa Crop Improvement Association, no effort was made to simulate potential yield using a photosynthesis model. The recorded plot yields were used as the maximum potential yields. This resulted in three advantages:

1. A simpler model that was less costly to run.
2. Less weather data required to run the model.
3. Accurate yield predictions.
The first step in determining potential yield was to define a full, medium, and short season variety hybrid for central Iowa conditions. Table 1 accomplishes this and lists a widely-planted pedigree of each classification. Table 2 tabulates the maximum potential yield for each variety over the 18 years in the data file.

Table 1. Definition of corn varieties

<table>
<thead>
<tr>
<th>Corn variety</th>
<th>Growth-degree-unit requirement planting to silking</th>
<th>Example pedigree</th>
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</thead>
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<tr>
<td>Full</td>
<td>1420</td>
<td>B73 x Mo17</td>
</tr>
<tr>
<td>Medium</td>
<td>1320</td>
<td>A632 x A619</td>
</tr>
<tr>
<td>Short</td>
<td>1250</td>
<td>W64A x W117</td>
</tr>
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</table>

The second step in determining potential yield was to adjust the yield response of each variety for the date of planting. Figure 2 graphically displays the 5-year average results of the Pioneer study. Table 3 tabulates the daily yield reduction coefficients used in the CORNSIM model.

Simulation of Plant Development

The plant development is divided into 3 phases. Phase 1, the vegetative growth stage, begins with planting and extends to flowering (silking). It is simulated by the accumulation of growing degrees (GDs). The number of GDs occurring daily are calculated using the following formula:
Table 2. Maximum potential yield for the three corn varieties

<table>
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<tr>
<th>Growing season</th>
<th>Variety yield (Bu/Ac)</th>
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<tr>
<td></td>
<td>Full</td>
<td>Medium</td>
<td>Short</td>
</tr>
<tr>
<td>1958</td>
<td>125</td>
<td>115</td>
<td>105</td>
</tr>
<tr>
<td>1959</td>
<td>135</td>
<td>125</td>
<td>115</td>
</tr>
<tr>
<td>1960</td>
<td>115</td>
<td>105</td>
<td>95</td>
</tr>
<tr>
<td>1961</td>
<td>135</td>
<td>125</td>
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<td>1962</td>
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<td>1974</td>
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</tr>
<tr>
<td>1975</td>
<td>130</td>
<td>130</td>
<td>120</td>
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</tbody>
</table>

Table 3. Daily yield reductions due to late planting

<table>
<thead>
<tr>
<th>Corn variety</th>
<th>Yield reductions (Bu/Ac/Day)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>May 5-15</td>
<td>May 15-25</td>
<td>After May 25</td>
</tr>
<tr>
<td>Full</td>
<td>0.5</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Medium</td>
<td>0.0</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Short</td>
<td>0.0</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Figure 2. Yield response versus planting date for three varieties of corn.
where GD = daily growing degrees.

TMAX = maximum daily temperature, °F. If the maximum temperature is greater than 86°F, TMAX is set equal to 86°F before the calculation is made.

TMIN = minimum daily temperature, °F. If the minimum temperature is less than 50°F, TMIN is set equal to 50°F before the calculation is made.

Table 1 tabulates the number of GDs required by each variety to reach flowering.

Phase 2, the ear growth stage, begins with flowering and progresses through the "kernel setting" and "water blister" stages and terminates when the grain reaches 75% MCWB. Many researchers have commented that the correlation between accumulated growing degree days and plant development is very good during the vegetative growth stage but then tends to decline. Schmidt and Hallauer (1966) studied the correlation between four weather factors and the development of corn from a kernel moisture of 88 to 75%. They reported that only calendar days provided a statistically significant correlation. Based on Schmidt and Hallauer's data CORNSIM accumulates 22 calendar days to simulate Phase 2 development.

Phase 3, the dry-down stage, is simulated by using a 5-stage algorithm developed by a trial-and-error simulation technique to reproduce 8 years of local data (Schmidt, 1968a). The simulation began by using the 4 dry-down equations reported by Schmidt and Hallauer (1966) and illustrated in Figure 3.
A fifth relationship was added to cover the range below 20% MCWB. It predicted drying based on the difference between existing grain moisture and equilibrium moisture content of the daily weather.

Early tests showed there are three major problems with the algorithm. First, Schmidt arbitrarily selected the transition points between the dry-down equations at 75, 50, 30, 25, and 20 percent MCWB. The 30% MCWB transition point was the dividing line between whether dry bulb temperature or wet bulb depression was the driving dry-down force. Repeated runs demonstrated that corn makes the physiological change from maturing (temperature-driving force) to drying (wet bulb depression-driving force)
between 35 and 40% MCWB. This tends to correlate with the earlier stages of black layer development (Rench and Shaw, 1971). CORNSIM uses 37% MCWB as the transition point.

Second, the Schmidt equations were developed using long-term averages of drying rates for several years. When used to predict daily drying based on 24-hour average weather data the equations tended to over-predict field drying. This problem was corrected by multiplying the equations by a modification factor to account for the extremes of daily weather averages.

Third, the Schmidt equations were not designed to predict the rewetting of the crop in the moisture range of 25-20% MCWB on extremely humid days. An equilibrium moisture equation was substituted to determine the amount, if any, of rewetting. Figure 4 outlines the final dry-down algorithm. Figures 5-13 graphically illustrate how closely the CORNSIM algorithm predicted dry-down for 9 test years.

Predicting Freeze Damage

Corn kernels continue to accumulate dry matter until a black layer develops near the base of the kernel. The time when this black layer begins to develop depends on weather, the hybrid genetics, and the date of planting. Full season corn tends to reach black layer at a higher moisture content. Also, delayed planting of all varieties will increase kernel moisture at development of black layer. Rench and Shaw (1971) report the range of complete black layer development was from a high of 36.7% MCWB to a low of 27.6% MCWB for the central Iowa study.
Grain Moisture

<table>
<thead>
<tr>
<th>Moisture</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>75% MCWB</td>
<td>$R = 1.0 \left( -2.0 + 0.47 \text{ DBT} \right)$</td>
</tr>
<tr>
<td>50% MCWB</td>
<td>$R = 0.9 \left( -0.54 + 0.021 \text{ DBT} \right)$</td>
</tr>
<tr>
<td>37% MCWB</td>
<td>$R = 0.8 \left( -0.08 + 0.119 \text{ WBD} \right)$</td>
</tr>
<tr>
<td>25% MCWB</td>
<td>$R = 0.8 \left( -0.432 + 0.146 \text{ WBD} \right)$</td>
</tr>
<tr>
<td></td>
<td>If $R &lt; 0.0$ then $R = \text{the lesser of } 0.0 \text{ or } 0.05 \left( \text{GMC} - \left( \text{EMC} + 1.0 \right) \right)$</td>
</tr>
<tr>
<td>20% MCWB</td>
<td>$R = 0.05 \left( \text{GMC} - \left( \text{EMC} + 1.0 \right) \right)$</td>
</tr>
</tbody>
</table>

Equilibrium Moisture

$R = \text{Kernel Moisture Reduction} \ (\% \text{ MCWB/Day})$

DBT = Dry Bulb Temperature (°F)

WBD = Wet Bulb Depression

GMC = Grain Moisture Content

EMC = Equilibrium Moisture Content

Figure 4. CORNSIM field dry-down algorithm

CORNSIM uses 33% MCWB as the termination point of dry matter accumulation. CORNSIM computes a 2.5% yield reduction for each percent of moisture above 33% MCWB when the first freeze occurs. This is a slightly more severe yield reduction than indicated by data gathered by Schmidt (1968b) as plotted in Figure 14.
Figure 5. Grain moisture versus calendar date for 1958
Figure 6. Grain moisture versus calendar date for 1959
Figure 7. Grain moisture versus calendar date for 1960
Figure 8. Grain moisture versus calendar date for 1961
Figure 9. Grain moisture versus calendar date for 1964
Figure 10. Grain moisture versus calendar date for 1965
Figure 11. Grain moisture versus calendar date for 1966
Figure 12. Grain moisture versus calendar date for 1967
Figure 13. Grain moisture versus calendar date for 1968
Figure 14. Percent of maximum dry weight versus kernel moisture

SLOPE = $\frac{-46}{20} = -2.3$
Simulation of Harvest

Harvest begins as soon as the driest of all the fields reaches the user-defined "beginning harvest moisture" or when the user-supplied "day to begin harvest regardless of moisture" is reached. Harvest can only proceed on "go" field days at whichever is the most restrictive of the user-supplied harvest rates. Once begun, harvesting occurs in the driest field first and then proceeds to the next driest field until all the crop is harvested or no more "go" field days are available. The total quantity harvested per day is determined by the availability of dry grain in the field, the effective harvesting rates, and the user-supplied "work time" strategy.

The actual bushels per acre harvested is maximum potential yield minus the delayed planting loss, freeze damage loss, preharvest loss, and combine loss. The preharvest loss coefficients are tabulated in Table 4. They were developed from a 5-year study reported by Pioneer Seed Company (1974 and 1975) as shown in Table 5.

Table 4. Preharvest field loss coefficients

<table>
<thead>
<tr>
<th>Date</th>
<th>Loss (bushel/acre/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before October 1</td>
<td>0.0</td>
</tr>
<tr>
<td>October 1 to November 16</td>
<td>0.2</td>
</tr>
<tr>
<td>After November 16</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Table 5. Combine harvest yields

<table>
<thead>
<tr>
<th>Harvest date</th>
<th>5-year average for 9 hybrids (bushels/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 19</td>
<td>143</td>
</tr>
<tr>
<td>September 30</td>
<td>145</td>
</tr>
<tr>
<td>October 10</td>
<td>143</td>
</tr>
<tr>
<td>October 22</td>
<td>142</td>
</tr>
<tr>
<td>November 6</td>
<td>139</td>
</tr>
<tr>
<td>November 19</td>
<td>135</td>
</tr>
</tbody>
</table>

^Test at Johnston, Iowa.

The combine harvest loss was assumed to be 2 bushels per acre before November 16 and 4 bushles per acre after that date. The date harvesting is completed, the freeze damage loss, total field loss, harvested yield, and moisture content on the finishing day are all reported in the field summaries.
User Inputs

The exact format of user supplied input to CORNSIM is given in Appendix A. The first page of output printed by CORNSIM is an "echo check" of the user-defined inputs; see Figure 15. The user must also supply 18 disk data sets as outlined in Appendix B for cropping seasons 1958-1975 and then assign these data sets to I/O units 8-25, respectively.

Local Calibration Coefficients and Key Internal Variables

All of the CORNSIM calibration coefficients as explained in the previous major section (Development of CORNSIM) can be easily changed to reflect special local conditions in the block data subroutine. See Appendix C and the program listing in Appendix E.

The definitions of the key internal variables are given in Appendix D. This information is valuable to anyone wishing to understand the internal functioning of the CORNSIM code.

Output

CORNSIM offers three levels of printed output. Level 1 prints a copy of the input data as displayed in Figure 15. Level 2 also includes the actual acres planted and harvested, total harvested yield, and a detailed log of each field (Figure 16); plus the complete record of the simulated harvest grain flow (Figure 17). Level 3 includes all of the previously mentioned information plus a daily log of grain moisture in
SIMULATED CORN PRODUCTION FOR A TYPICAL CENTRAL IOWA FARM

STARTING WITH THE 1968 PRODUCTION SEASON
FINISHING WITH THE 1968 PRODUCTION SEASON

FIRST ALLOWABLE JULIAN DAY TO BEGIN PLANTING - 116
LAST JULIAN DAY TO PLANT FULL SEASON CORN - 134
LAST JULIAN DAY TO PLANT MEDIUM SEASON CORN - 148
LAST JULIAN DAY TO PLANT SHORT SEASON CORN - 155

A MINIMUM OF 15 GOOD SPRING FIELD DAYS MUST OCCUR BEFORE PLANTING CAN BEGIN.

PLANTING RATE IS 5.00 ACRES PER HOUR.

PLANTING STRATEGY
NO. AC. VARIETY
300  1
  0  0
  0  0
  0  0
  0  0

TIME AVAILABLE FOR FIELD OPERATIONS
JULIAN DATE HOURS PER DAY
  92  7
 121 3
 135 9
 170 8
  0  0
  0  0

HARVEST WILL BEGIN WHEN THE CORN DRIES DOWN TO 24.0 PERCENT MCWB.
HARVEST WILL BEGIN REGARDLESS OF MOISTURE ON JULIAN DATE 305.
HARVEST RATE IS THE LESSER OF 2.50 ACRES PER HOUR OR 300.00 BUSHELS PER HOUR.

OUTPUT OPTIONS IN EFFECT
IPRINT = 2
IPUNCH = 0

Figure 15. Output check on user-supplied inputs
1968 PRODUCTION SEASON

ACRES PLANTED = 300.0
ACRES HARVESTED = 300.0
BUSHELS HARVESTED = 39833.7

*** 1968 FIELD NUMBER 1 - FULL SEASON CORN

PLANTING DATE(JULIAN) = 118
SILKING DATE(JULIAN) = 200
MATURITY DATE(JULIAN) = 269
HARVESTING DATE(JULIAN) = 289

FIELD SIZE (ACRES) = 35.0000
POTENTIAL YIELD (BU) = 140.0000
PLANTING LOSS (BU) = 0.0
FREEZE LOSS (BU) = 0.0
FIELD LOSS (BU) = 5.0000
HARVESTED YIELD (BU) = 135.0000
HARVESTED MOISTURE = 23.0618
ACRES LEFT IN FIELD = 0.0

*** 1968 FIELD NUMBER 2 - FULL SEASON CORN

PLANTING DATE(JULIAN) = 115
SILKING DATE(JULIAN) = 201
MATURITY DATE(JULIAN) = 270
HARVESTING DATE(JULIAN) = 301

FIELD SIZE (ACRES) = 35.0000
POTENTIAL YIELD (BU) = 140.0000
PLANTING LOSS (BU) = 0.0
FREEZE LOSS (BU) = 0.0
FIELD LOSS (BU) = 9.4000
HARVESTED YIELD (BU) = 130.6000
HARVESTED MOISTURE = 18.6098
ACRES LEFT IN FIELD = 0.0

*** 1968 FIELD NUMBER 3 - FULL SEASON CORN

PLANTING DATE(JULIAN) = 125
SILKING DATE(JULIAN) = 204
MATURITY DATE(JULIAN) = 271
HARVESTING DATE(JULIAN) = 311

FIELD SIZE (ACRES) = 35.0000
POTENTIAL YIELD (BU) = 140.0000
PLANTING LOSS (BU) = 0.0
FREEZE LOSS (BU) = 0.0
FIELD LOSS (BU) = 9.4000
HARVESTED YIELD (BU) = 130.6000
HARVESTED MOISTURE = 18.6098
ACRES LEFT IN FIELD = 0.0

Figure 16. CORNSIM output-year summary
HARVESTED GRAIN FLOW FOR THE 1968 CROP SEASON

<table>
<thead>
<tr>
<th>JULIAN DATE</th>
<th>BUSHELS</th>
<th>MOISTURE TEMPERATURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>288</td>
<td>2400.0</td>
<td>23.59</td>
</tr>
<tr>
<td>289</td>
<td>2328.6</td>
<td>23.06</td>
</tr>
<tr>
<td>289</td>
<td>71.4</td>
<td>23.59</td>
</tr>
<tr>
<td>293</td>
<td>2400.0</td>
<td>22.71</td>
</tr>
<tr>
<td>294</td>
<td>2222.7</td>
<td>22.20</td>
</tr>
<tr>
<td>294</td>
<td>177.3</td>
<td>22.20</td>
</tr>
<tr>
<td>295</td>
<td>2400.0</td>
<td>21.69</td>
</tr>
<tr>
<td>296</td>
<td>2400.0</td>
<td>21.27</td>
</tr>
<tr>
<td>297</td>
<td>370.2</td>
<td>21.12</td>
</tr>
<tr>
<td>297</td>
<td>2029.8</td>
<td>21.14</td>
</tr>
<tr>
<td>300</td>
<td>2400.0</td>
<td>27.38</td>
</tr>
<tr>
<td>301</td>
<td>227.0</td>
<td>20.21</td>
</tr>
<tr>
<td>301</td>
<td>2173.0</td>
<td>20.36</td>
</tr>
<tr>
<td>302</td>
<td>2400.0</td>
<td>20.06</td>
</tr>
<tr>
<td>303</td>
<td>725.2</td>
<td>19.67</td>
</tr>
<tr>
<td>303</td>
<td>1674.8</td>
<td>19.67</td>
</tr>
<tr>
<td>304</td>
<td>2400.0</td>
<td>19.35</td>
</tr>
<tr>
<td>305</td>
<td>1205.9</td>
<td>19.00</td>
</tr>
<tr>
<td>305</td>
<td>1194.1</td>
<td>19.10</td>
</tr>
<tr>
<td>308</td>
<td>2400.0</td>
<td>18.61</td>
</tr>
<tr>
<td>309</td>
<td>1656.8</td>
<td>18.53</td>
</tr>
<tr>
<td>309</td>
<td>743.2</td>
<td>18.53</td>
</tr>
<tr>
<td>310</td>
<td>2400.0</td>
<td>13.67</td>
</tr>
<tr>
<td>311</td>
<td>1433.7</td>
<td>18.61</td>
</tr>
</tbody>
</table>

Figure 17. CORNSIM output-simulated harvest grain flow
each field (see Figure 18). The zeros near the bottom of each field column indicate the field has been harvested. A "1" value in the "frost damage array" indicates that the yield in that specific field was reduced due to freeze damage.

Machine Requirements

CORNsIM was designed to run on the IBM Compatible FORTRAN H Compiler at Iowa State University. The program required approximately 100K of core. Simulation of 18 cropping seasons executes in about 30 seconds at a cost of roughly seven dollars.
### Figure 18. CORNSIM output-date versus grain moisture table

#### DATE VS GRAIN MOISTURE TABLE

**DATE/PLACE**  | 1 - 30 FIELDS
---|---
09/10/68DMI 74 | 0. 0. 0. 0. 0. 0. 0.
08/11/68DMI 73 | 0. 0. 0. 0. 0. 0. 0.
08/12/68DMI 72 | 73. 74. 74. 0. 0. 0. 0.
08/13/68DMI 70 | 71. 72. 72. 74. 0. 0. 0.
08/14/68DMI 69 | 70. 71. 71. 72. 74. 74. 74.
08/15/68DMI 67 | 68. 69. 69. 71. 71. 72. 72.
08/16/68DMI 66 | 67. 68. 68. 69. 69. 70. 70.
08/17/68DMI 65 | 66. 67. 67. 68. 68. 69. 69.
08/18/68DMI 63 | 64. 65. 67. 67. 68. 68. 68.
08/19/68DMI 61 | 63. 64. 64. 65. 65. 66. 66.
08/20/68DMI 60 | 61. 62. 62. 63. 63. 64. 64.
08/21/68DMI 59 | 60. 61. 61. 62. 62.
08/22/68DMI 59 | 60. 61. 61. 62. 62.
08/23/68DMI 59 | 60. 61. 61. 62. 62.
08/24/68DMI 59 | 60. 61. 61. 62. 62.
08/25/68DMI 59 | 60. 61. 61. 62. 62.
08/26/68DMI 59 | 60. 61. 61. 62. 62.
08/27/68DMI 59 | 60. 61. 61. 62. 62.
08/28/68DMI 59 | 60. 61. 61. 62. 62.
08/29/68DMI 59 | 60. 61. 61. 62. 62.
08/30/68DMI 59 | 60. 61. 61. 62. 62.
09/01/68DMI 28 | 29. 29. 25. 25. 25.
10/02/68DMI 28 | 29. 29. 25. 25. 25.
10/03/68DMI 27 | 28. 28. 28. 29. 29. 25.
10/04/68DMI 27 | 27. 27. 27. 28. 28. 28.

**FREEZE DAMAGE ARRAY = 00000 000**

10/05/68DMI 27 | 27. 27. 27. 28. 28. 28.
10/06/68DMI 26 | 27. 27. 27. 28. 28. 28.
10/07/68DMI 26 | 27. 26. 26. 27. 27. 27.
10/08/68DMI 26 | 26. 26. 26. 27. 27. 27.
10/09/68DMI 25 | 26. 25. 25. 26. 27. 27.
10/11/68DMI 25 | 24. 25. 25. 25. 25. 25.
10/12/68DMI 25 | 24. 25. 25. 25. 25. 25.
10/13/68DMI 25 | 24. 25. 25. 25. 25. 25.
10/14/68DMI 25 | 25. 25. 25. 25. 25. 25.
10/17/68DMI 23 | 23. 23. 23. 23. 23. 23.
10/18/68DMI 22 | 22. 22. 22. 22. 22. 22.
10/20/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/21/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/22/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/23/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/24/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/25/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/26/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/27/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/28/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/29/68DMI 0  | 0. 0. 0. 0. 0. 0.
10/30/68DMI 0  | 0. 0. 0. 0. 0. 0.
11/01/68DMI 0  | 0. 0. 0. 0. 0. 0.
11/02/68DMI 0  | 0. 0. 0. 0. 0. 0.
11/03/68DMI 0  | 0. 0. 0. 0. 0. 0.
11/04/68DMI 0  | 0. 0. 0. 0. 0. 0.
11/05/68DMI 0  | 0. 0. 0. 0. 0. 0.
11/06/68DMI 0  | 0. 0. 0. 0. 0. 0.
11/07/68DMI 0  | 0. 0. 0. 0. 0. 0.

Figure 18. CORNSIM output-date versus grain moisture table
VALIDATION OF CORNSIM

Concepts and data from a large variety of independent sources were included in the development of CORNSIM. The basic question was yet to be answered, "Were CORNSIM results representative of central Iowa conditions?". "Base Management Strategy" typical of central Iowa farmers was developed and simulated using CORNSIM for cropping seasons 1967-1975. The simulated results produced by CORNSIM were then compared with the actual central Iowa data as reported by the Iowa Crop and Livestock Reporting Service (ICLRS).

Table 6 outlines the "Base Management Strategy". Figures 19 and 20 graphically compare CORNSIM results with actual central Iowa observations as reported by the ICLRS. CORNSIM provides a specific completion date for each of 4 events, whereas the observations provide the percent of farmers that are completed out of a large sample. Assuming the "Base Management Strategy" is typical and CORNSIM is a valid model, the specific dates simulated by CORNSIM should approximate the 50% completion observation. With the exception of the "maturity" event, a close correlation exists. Planting, silking, and harvesting can be accurately observed and recorded, whereas the occurrence of maturity is a subjective observation. CORNSIM's definition of maturity (grain moisture < 33% MCWB) is more conservative than the visual assessment used by the Iowa Crop and Livestock Reporting Service. Therefore, the dates reported by CORNSIM are somewhat later.

The high degree of correlation between the observed and simulated
Table 6. Base management strategy

<table>
<thead>
<tr>
<th>Area of corn production</th>
<th>300 acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum field days for tillage before planting may begin</td>
<td>15</td>
</tr>
<tr>
<td>Earliest possible day planting may begin</td>
<td>April 26</td>
</tr>
<tr>
<td>Last day to plant full season corn</td>
<td>May 14</td>
</tr>
<tr>
<td>Last day to plant medium season corn</td>
<td>May 28</td>
</tr>
<tr>
<td>Last day to plant short season corn</td>
<td>June 3</td>
</tr>
<tr>
<td>Effective planting rate</td>
<td>5 acres/hour</td>
</tr>
<tr>
<td>Hybrid selection</td>
<td>full season</td>
</tr>
<tr>
<td>Effective field working time</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>7 hours/day</td>
</tr>
<tr>
<td>May 1-14</td>
<td>8 hours/day</td>
</tr>
<tr>
<td>May 15-June</td>
<td>9 hours/day</td>
</tr>
<tr>
<td>Fall harvest season</td>
<td>8 hours/day</td>
</tr>
<tr>
<td>Begin harvest as soon as the grain moisture in the field reaches</td>
<td>24% MCWB</td>
</tr>
<tr>
<td>Or the arrival of</td>
<td>November 1</td>
</tr>
<tr>
<td>Grain harvesting rate equals</td>
<td>2.5 acres/hour</td>
</tr>
<tr>
<td>But is limited to a maximum of</td>
<td>300 bushels/hour</td>
</tr>
</tbody>
</table>

results is further illustrated by the relative ranks of the 9 cropping seasons as given in Table 7. CORNSIM is particularly useful in pointing out the significantly "earlier" and "later" seasons at each stage of crop progress. It is also interesting to note that the relative ranking of seasons may change significantly at progressive stages of crop development. For example, 1972 was a typical year at planting time while 1975 was delayed; but, by harvest time, 1975 was a very early year while 1972 was the latest.
**Comparison of CORNSIM to Actual Observations - Part I**

<table>
<thead>
<tr>
<th>CROPPING SEASON</th>
<th>PLANTING DATE</th>
<th>SILKING DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>APR 30</td>
<td>MAY 10</td>
</tr>
<tr>
<td>67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 19.** Comparison of CORNSIM to actual observations - Part I

- **SIMULATED COMPLETION DATE**
- **OBSERVED 20-70% COMPLETED**
### COMPARISON OF CORNSIM TO ACTUAL OBSERVATIONS - PART II

<table>
<thead>
<tr>
<th>CROPPING SEASON</th>
<th>MATURITY DATE</th>
<th>HARVESTING DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SEPT 10</td>
<td>SEPT 20</td>
</tr>
<tr>
<td>67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>71</td>
<td></td>
<td></td>
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<tr>
<td>72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- ■: SIMULATED COMPLETION DATE
- □: OBSERVED 20-70% COMPLETED
- —: OBSERVED 50-90% COMPLETED

Figure 20. Comparison of CORNSIM to actual observations - Part II
<table>
<thead>
<tr>
<th>Relative ranking</th>
<th><strong>Planting</strong></th>
<th><strong>Silking</strong></th>
<th><strong>Maturing</strong></th>
<th><strong>Harvesting</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Earliest</td>
<td>71 — 71</td>
<td>70 — 70</td>
<td>70 — 70</td>
<td>71 — 71</td>
</tr>
<tr>
<td></td>
<td>70 68</td>
<td>71 — 71</td>
<td>71 — 71</td>
<td>75 — 75</td>
</tr>
<tr>
<td></td>
<td>68 67</td>
<td>75 — 74</td>
<td>75 — 72</td>
<td>70 — 70</td>
</tr>
<tr>
<td></td>
<td>74 70</td>
<td>72 — 75</td>
<td>72 — 74</td>
<td>74 — 74</td>
</tr>
<tr>
<td></td>
<td>67 74</td>
<td>74 — 72</td>
<td>68 — 75</td>
<td>73 — 69</td>
</tr>
<tr>
<td></td>
<td>72 — 72</td>
<td>68 — 73</td>
<td>74 — 73</td>
<td>69 — 73</td>
</tr>
<tr>
<td></td>
<td>69 — 69</td>
<td>73 — 68</td>
<td>73 — 69</td>
<td>68 — 67</td>
</tr>
<tr>
<td></td>
<td>75 — 75</td>
<td>67 — 67</td>
<td>69 — 68</td>
<td>67 — 68</td>
</tr>
<tr>
<td>Latest</td>
<td>73 — 73</td>
<td>69 — 69</td>
<td>67 — 67</td>
<td>72 — 72</td>
</tr>
</tbody>
</table>

*a* Observation data reported by the Iowa Crop and Livestock Reporting Service (1958-1975).

*b* Simulation results generated by CORNSIM using "Base Management Strategy".
USES AND RESULTS OF CORNSIM

CORNSIM opens a wide variety of areas for potential study due to
the ability to simulate the integrated effects of weather, hybrid selec­
tion, labor availability, machine capacity, and management strategy. For
example, Figure 21 illustrates the effect of varying planting dates of
a medium season corn for the 1968 production season. It shows that medium
season corn planted after the fourth week of May is likely to be damaged
by a freeze and fail to adequately field dry. Corn moisture in the field
remains reasonably constant after early November.

Figure 22 illustrates the effect of weather for a medium season vari­
ety planted on May 15 for years of 1967 and 1971-1973. It shows that
crop conditions on September 1 are a questionable indicator of what kind
of harvest season one should expect. For example the "very early" devel­
oping crop of 1973 resulted in an "average" harvest season while the
"slightly later" developing crop of 1971 ended up being a "very early"
harvest season. Conversely, the "very late" developing crop of 1967 re­
sulted in only slightly higher than average field moisture by early Novem­
ber. The 1972 harvest season was probably the worst in the last quarter
century. Strangely, it was a typical season until mid-September but then,
due to unusually cool damp weather, the crop failed to dry normally.

Figures 23 and 24 illustrate the cumulative bushels harvested and
the daily harvest moisture versus the harvest date for years 1967-1975
assuming the "base" management strategy outlined in the previous section.
This is the information needed to simulate the performance of grain
Figure 21. The effect of varying planting date on corn development for a medium season variety in 1968
Figure 22. The effect of 1967, 1971, 1972, and 1973 weather on corn development for long season variety planted on May 15.
Figure 23. Cumulative harvested yield versus harvest date using "base" management strategy
Figure 24. Daily harvest moisture versus harvest date using "base" management strategy.
drying and storage systems, particularly low-temperature drying systems.

CORN$IM can also be used to predict the relative value of changes in the farm manager's operating strategy. Table 8 outlines several alternatives to the "base" management strategy. Table 9 outlines the management inputs and gives summary results of 18 different CORNSIM runs. The "Income" column is an estimate of the cash value of the crop at harvest time, assuming delivery to an elevator for $2.50 per bushel at 15.5% MCW minus a drying charge of 1-3/4¢ per point of moisture above 15.5 percent. The average income is useful in comparing the alternate management strategies, but it does not account for the value of additional fall field days available for tillage after harvest is completed.

Figure 25 illustrates that planting strategy is a critical parameter in determining the amount of corn harvested and the annual income. A more detailed analysis could determine the dollar return for increasing specific machine capacities and/or the marginal value of additional labor. Figure 26 illustrates the importance of hybrid selection. A farm manager must weigh the benefits of earlier harvest against the yield reduction associated with planting shorter season varieties. Figure 27 shows that the decreased field losses due to beginning harvest at a higher moisture content approximately cover the increase in drying cost. Figure 28 illustrates that increasing harvesting rate increases net yield. But the higher average grain moisture resulting from rapid harvest increases drying cost and tends to offset the expected increase in income.
Table 8. Alternate management strategies

<table>
<thead>
<tr>
<th>Planting</th>
<th>Early</th>
<th>Base</th>
<th>Late</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum field days</td>
<td>8</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>First planting day</td>
<td>Apr. 19</td>
<td>Apr. 26</td>
<td>May 3</td>
</tr>
<tr>
<td>Effective field time (hours/day)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>10</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>May 1-14</td>
<td>11</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>May 15-June</td>
<td>12</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

| Hybrid selection           |       |      |       |
| Med.                       | - All crop area planted with a medium season hybrid |
| Base                       | - All crop area planted with a full season hybrid |
| Comb.                      | - 1/3 of crop area planted with medium season hybrid first followed by the remaining 2/3 planted with full season hybrid |

<table>
<thead>
<tr>
<th>Harvest moisture</th>
<th>High</th>
<th>Base</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning harvest (MCWB)</td>
<td>26%</td>
<td>24%</td>
<td>22%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Harvest capacity</th>
<th>Slow</th>
<th>Base</th>
<th>Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective field time (hours/day)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall season</td>
<td>4</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>
Table 9. CORNSIM results

<table>
<thead>
<tr>
<th>CORNSIM Run No.</th>
<th>Planting strategy</th>
<th>Hybrid selection</th>
<th>Harvest moisture</th>
<th>Harvest capacity</th>
<th>Harvested corn (bu./yr.)</th>
<th>Income ($/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base</td>
<td>Base</td>
<td>Low</td>
<td>Base</td>
<td>37260</td>
<td>90370</td>
</tr>
<tr>
<td>2</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>37660</td>
<td>90360</td>
</tr>
<tr>
<td>3</td>
<td>Base</td>
<td>Base</td>
<td>High</td>
<td>Base</td>
<td>37930</td>
<td>89870</td>
</tr>
<tr>
<td>4</td>
<td>Base</td>
<td>Med.</td>
<td>Low</td>
<td>Base</td>
<td>35240</td>
<td>85450</td>
</tr>
<tr>
<td>5</td>
<td>Base</td>
<td>Med.</td>
<td>Base</td>
<td>Base</td>
<td>35660</td>
<td>87150</td>
</tr>
<tr>
<td>6</td>
<td>Base</td>
<td>Med.</td>
<td>High</td>
<td>Base</td>
<td>35880</td>
<td>84940</td>
</tr>
<tr>
<td>7</td>
<td>Base</td>
<td>Comb.</td>
<td>Low</td>
<td>Base</td>
<td>36650</td>
<td>88570</td>
</tr>
<tr>
<td>8</td>
<td>Base</td>
<td>Comb.</td>
<td>Base</td>
<td>Base</td>
<td>37070</td>
<td>88460</td>
</tr>
<tr>
<td>9</td>
<td>Base</td>
<td>Comb.</td>
<td>High</td>
<td>Base</td>
<td>37280</td>
<td>87800</td>
</tr>
<tr>
<td>10</td>
<td>Base</td>
<td>Base</td>
<td>Low</td>
<td>Fast</td>
<td>37480</td>
<td>90460</td>
</tr>
<tr>
<td>11</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>Fast</td>
<td>37870</td>
<td>90170</td>
</tr>
<tr>
<td>12</td>
<td>Base</td>
<td>Base</td>
<td>High</td>
<td>Fast</td>
<td>38110</td>
<td>89370</td>
</tr>
<tr>
<td>13</td>
<td>Base</td>
<td>Comb.</td>
<td>Low</td>
<td>Fast</td>
<td>36820</td>
<td>88510</td>
</tr>
<tr>
<td>14</td>
<td>Base</td>
<td>Comb.</td>
<td>Base</td>
<td>Fast</td>
<td>37210</td>
<td>88140</td>
</tr>
<tr>
<td>15</td>
<td>Base</td>
<td>Comb.</td>
<td>High</td>
<td>Fast</td>
<td>37410</td>
<td>87250</td>
</tr>
<tr>
<td>16</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>Slow</td>
<td>36780</td>
<td>89380</td>
</tr>
<tr>
<td>17</td>
<td>Early</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>38370</td>
<td>92215</td>
</tr>
<tr>
<td>18</td>
<td>Late</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>35980</td>
<td>86260</td>
</tr>
</tbody>
</table>

^aAverage over 18 years of simulated results.

^b"Base run."
Figure 25. Effect of planting strategy using 18 years of CORNSIM results
Figure 26. Effect of hybrid selection using 18 years of CORNSIM results
Figure 27. Effect of beginning harvest moisture using 18 years of CORNSIM results.
Figure 28. Effect of harvest rate using 18 years of CORNSIM results.
CONCLUSIONS

Development of CORNSIM provided several valuable results. It forced a high level of systematic analysis. In addition to the typical engineering subject areas of machinery capacities and operations management, it necessitated study of corn genetics, the physiological stages of corn development, weather, and their interactions. The development of optimum management strategies for a complete corn production system is significantly more complex than simply maximizing the output of each individual plant or machine component.

The development of CORNSIM was successful. CORNSIM is a valid simulation model of corn production systems for central Iowa conditions. It can be used to determine the relative effects of changes in production strategy. The most unique features of CORNSIM are the ability to simulate the dry-down phase of corn development and to predict harvest progress. CORNSIM supplied realistic harvested grain flow data that subsequently was used in a low-temperature corn drying and storage study.

CORN Simulation was developed to answer the question, "What if I had ... for the last ... years?". This "synthetic" experience combined with a farm manager's personal experience enhance his understanding and decision-making ability. CORNSIM is a valuable tool for researchers, extension staff, students, and farm managers alike.
SUGGESTIONS FOR FURTHER RESEARCH

Results of this project suggest the following tasks for future study and development:

1. Validate CORNSIM for other areas in the Midwest Corn Belt.
2. Gather field data on the dry-down characteristics of several of the newly developed "fast dry-down" hybrids in more than one geographical area.
3. Develop CORNSIM to include soybeans in the production system.
4. Incorporate Duncan's (1975) corn model into CORNSIM so that the yield predictions are sensitive to specific soil-water conditions.
5. Enhance the machinery simulation portion of CORNSIM to include the individual operations of the tillage, planting, and harvesting.
6. Develop an economic analysis program that uses CORNSIM results to determine the marginal value of changes in machine capacities and management strategies. Given actual costs of machinery and labor, the program could determine optimum machine sizes and management strategies.
REFERENCES


### APPENDIX A:
INPUT DATA FORMAT FOR CORNSIM

Note: The following format will be used throughout this section.

<table>
<thead>
<tr>
<th>Data card number</th>
<th>Variable name is</th>
<th>Fortran format</th>
</tr>
</thead>
<tbody>
<tr>
<td>(card image)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 1) Card 1
**MINFLD**

1 5

Minimum number of available field days needed before planting begins.

#### 2) Card 2
**JPLTST(5,2)**

5 0 1 5 0 2 1 0 0 1

Maximum of 5 sets of planting strategy—Number of acres, Variety identification integer, Number of acres, Variety identification integer. Total corn acres of farm equals the sum of the acres of 5 sets of plantings. Variety identification numbers are:

<table>
<thead>
<tr>
<th>Variety</th>
<th>Integer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full season corn</td>
<td>= 1</td>
</tr>
<tr>
<td>Medium season corn</td>
<td>= 2</td>
</tr>
<tr>
<td>Short season corn</td>
<td>= 3</td>
</tr>
</tbody>
</table>

#### 3) Card 3
**IPLTDY(5)**

1 1 6 1 3 4 1 4 8 1 5 5

Critical planting dates (Julian Date)
- First possible day to plant corn.
- Last day to plant full season variety.
- Last day to plant medium season variety.
- Last day to plant short season variety.
Maximum of 6 set of work time strategy - Julian Day, hours of available field time/day, Julian Day. The Julian date indicates the first day for the available field time that follows; unless changed by a subsequent date and time the available field time is effective for the rest of the year.

Last possible Julian Day to begin harvest regardless of grain moisture.

Grain moisture (percent MCWB) that begins harvest.

Specify the first and last modeling year (last two digits only). For 1 year simulation first and last year will be the same year.

Specify the planting rate in acres per hour, specify the maximums of harvest rate in acres per hour and bushels per hour. (Whichever of the two harvest rates is most limiting will be effective.)
Specify the print and punch options.

**Print Options**

<table>
<thead>
<tr>
<th>Integer</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Printed copy of the input strategy</td>
</tr>
<tr>
<td>1</td>
<td>All of the above plus simulated grain flow data, and yearly summaries of all fields.</td>
</tr>
<tr>
<td>2</td>
<td>All of the above plus a daily log of corn moisture in each field.</td>
</tr>
</tbody>
</table>

**Punch Options**

<table>
<thead>
<tr>
<th>Integer</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No punched output.</td>
</tr>
<tr>
<td>1</td>
<td>Punched output of simulated harvest grain flow.</td>
</tr>
</tbody>
</table>

**Format of Punched Output** *(I5,4F10.2)*

Year, Julian Date, bushels, moisture, temperature
APPENDIX B:

WEATHER RELATED VARIABLES

There must be a separate disk data set for each crop season, i.e., (V.U3383.DAT58 for 1958 season) consisting of 275 card images beginning with April 1 and ending with December 31. The cards must contain the following information:

\[\text{IDAY}(3), \text{DB}, \text{WBDPRS}, \text{IFREZ}, \text{IGO}, \text{EQM}, \text{CUMCDU}\]

Format \((3A4,F6.1,12X,F6.1,20X,2I3,F6.4,6X,F6.0)\)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDAY(3)</td>
<td>12 space alpha numeric code of day, month, year, place.</td>
</tr>
<tr>
<td>DB</td>
<td>Average dry bulb temperature (^\circ\text{F}).</td>
</tr>
<tr>
<td>WBDPRS</td>
<td>Average wet bulb depression (^\circ\text{F}).</td>
</tr>
</tbody>
</table>
| IFREZ    | Either 0 or 1 integer  
            0 - minimum dry bulb temperature > 32\(^\circ\text{F}\)  
            1 - minimum dry bulb temperature < 32\(^\circ\text{F}\) |
| IGO      | Either 0 or 1 integer  
            0 - fields are not trafficable  
            1 - available field day |
| EQM      | Average equilibrium moisture content of corn as calculated using Thompson equilibrium moisture equation. |
| CUMCDU   | Cumulative growing degree units for the year, as computed by the Newman method. |
APPENDIX C:

VARIABLE SPECIFIC TO LOCAL CONDITIONS
(Initialized in block data subroutine)

**DDCOEF(5,3)**

3 coefficients for each of the five stages of the grain development and dry down algorithm.

**DDMST(5)**

The grain moisture at the beginning of 5 stages of the grain algorithm.

**YLDPLT(3,3)**

The yield penalties (bushels/acre/day) for plant the 3 varieties after 3 key dates (5 May, 15 May, and 25 May).

**YLDHAR(2)**

The field losses (bushels/acre/day) between, and after 2 key dates (1 October, 16 November).

**YLDCON(2)**

The combine losses (bushels/acre) before and after 16 November.

**ISLKDY(3)**

Number of calendar days from silking to grain moisture of DDMST(1) for 3 varieties.

**VTYCDU(3)**

Number of growing degree units needed to develop from planting to silking for each of 3 varieties.

**YLDPOT(18,3)**

Maximum potential yield for 3 varieties for years 1958 to 1975.

**FRZMST**

Grain moisture when grain becomes mature and freeze safe.

**FRZDMG**

Percent of yield loss for each percent of grain moisture above FRZMST at occurrence of first freeze.
APPENDIX D:

KEY INTERNAL VARIABLES

1. The program simulates on 24 hour increments 1 year at a time. It prints output on a continuous basis and reuses and reassigns the arrays for each successive year, with the exception of array HARLOT which collects the harvested grain flow data over the entire simulation period.

HARLOT(18,50,4)

18 years of simulation
50 lots* of harvested grain (max.)

4 Simulated Values
1 - Julian Day of harvest
2 - Quantity (bushels)
3 - Moisture (%MCWB)
4 - Temperature (°F)

2. CORNSIM can simulate a maximum of 30 fields during 1 crop season thus the dimension "30" in the following arrays:

IFLD(30,6)

1. Stage of crop development

<table>
<thead>
<tr>
<th>Integer Value</th>
<th>Explanation of Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Unplanted field</td>
</tr>
<tr>
<td>1</td>
<td>Planted field</td>
</tr>
<tr>
<td>2</td>
<td>Corn has silked</td>
</tr>
<tr>
<td>3</td>
<td>Corn has reached DDMST(1)</td>
</tr>
<tr>
<td>4</td>
<td>Corn has reached DDMST(2)</td>
</tr>
<tr>
<td>5</td>
<td>Corn has reached DDMST(3)</td>
</tr>
<tr>
<td>6</td>
<td>Corn has reached DDMST(4)</td>
</tr>
<tr>
<td>7</td>
<td>Corn has reached DDMST(5)</td>
</tr>
<tr>
<td>8</td>
<td>Field has been harvested</td>
</tr>
</tbody>
</table>

2. Julian Day planted
3. Julian Day silked
4. Julian Day grain matures
5. Julian Day harvested

*Note: 1 lot = 1 batch of grain harvest from 1 field on a specific day thus a lot of grain is homogenous.
6. Variety identification numbers:

<table>
<thead>
<tr>
<th>integer</th>
<th>Variety</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Long season corn</td>
</tr>
<tr>
<td>2</td>
<td>Medium season corn</td>
</tr>
<tr>
<td>3</td>
<td>Short season corn</td>
</tr>
</tbody>
</table>

I2FLD(30)
Julian Day corn reaches DDMST(5)
(development stage 3)

RFLD(30,7)
1. Field size (Acres)
2. Maximum yield potential (Bu/Ac)
3. Yield penalty due to late planting (Bu/Ac)
4. Yield penalty due to frost (Bu/Ac)
5. Yield penalty due to field and machine losses (Bu/Ac)
6. Actual yield (Bu/Ac)
7. Harvest moisture of grain.

S1FLD(30)
Cumulative growing degree units needed for field to reach "silk" stage.

S3FLD(30)
Grain moisture as crop progresses through development stages 3-7.

S4FLD(30)
Use to store the running tally of planted minus harvested acres.

3. Other variables

IPLTST(5,2)
Working sets of planting strategy modified by critical planting dates. IPLTST is renewed by JPLTST at the beginning of each year.

ACPLT(5)
The acres part of the planting strategy - reduced to zero as planting occurs. Renewed by JPLTST at the beginning of each year.
PLTACR
Total acres planted for the year.

HARACR
Total acres harvested for the year.

HARBUL
Total bushels harvested for the year.
APPENDIX E:
CORNSIM LISTING
//C227GRVE JOB U3383.VANEE
//ROUTE PRINT LOCAL
//JDBPARM LINES=15
//STEP1 EXEC FORTRAN,REGION,GO=140K
//FORTRAN SYSTIN DD *

BLOCK DATA
COMMON/GROW1/
1 IFLD(30,6),JPLTST(5,2),JYRSTR,LYRST,JMINFLD,IPRINT,IPUNCH
2 IHARDY,KJSKDY(3),IYRSTR,IYRST,PWDY(6,2),IDAY(3),
3 COMMON/GROW2/
1 RFLD(30,7),S1FLD(30),I2FLD(30),S3FLD(30),S4FLD(30),
2 YLDPOT(16,3),YLDPOT(3,3),YLDHAR(2),YLDCOM(2),ACPLT(5),
3 VTYGDU(3),DDMST(5),DDCOEF(5,3),HARLOT(18,50,4),HARMST,
4 PLTRAT,HARRAT(2),FRZMST,FRZDNG,PLTACR,HARACR,HARCAL
5 DATA DDCOEF/1.000,0.900,0.800,0.800,0.050,2.000,0.540,0.080,0.432,
6 1.000,0.047,0.021,0.119,0.146,0.000/
7 DATA DDMSK/75,50,37,25,20/
8 DATA YLDPOT/0.5,0.0,0.0,1.0,1.0,0.5,2.0,1.5,1.0/
9 DATA YLDHAR/0.20,0.50/
10 DATA YLDCOM/2.0,4.9/
11 DATA VTYGDU/1420,1320,1250/
12 DATA YLDPOT/125,135,115,120,135,125,115,140,130,140,
13 1,145,120,150,140,130,115,105,120,110,125,
14 215,110,130,120,135,120,145,135,140,120,130,105,1
15 315,955,115,100,115,105,105,120,110,120,125,110,130,12,
16 45,130,120,120,
17 DATA IFLO/180*0/
18 DATA RFLD/210*0/
19 DATA S1FLD/30*0/
20 DATA I2FLD/30*0/
21 DATA S3FLD/30*0/
22 DATA S4FLD/30*0/
23 DATA HARLOT/3600*0.0/
24 DATA FRZMST/33/
25 DATA FRZDNG/2,5/
26 C
27 COMMON/GROW1/
28 1 IFLD(30,6),JPLTST(5,2),JYRSTR(3),IYRST,JMINFLD,IPRINT,IPUNCH
29 COMMON/GROW2/
30 1 RFLD(30,7),S1FLD(30),I2FLD(30),S3FLD(30),S4FLD(30),
31 2 YLDPOT(16,3),YLDPOT(3,3),YLDHAR(2),YLDCOM(2),ACPLT(5),
32 3 VTYGDU(3),DDMST(5),DDCOEF(5,3),HARLOT(18,50,4),HARMST,
33 4 PLTRAT,HARRAT(2),FRZMST,FRZDNG,PLTACR,HARACR,HARCAL
34 C READ THE MINIMUM NUMBER OF FIELD DAYS NEEDED BEFORE PLANTING BEGINS
35 READ(5,1000)MINFLD
36 C READ ** IN PLANTING STRATEGY MAX OF 5 SETS OF (NO. AC. VAR.ID)
37 READ(5,1000)(JPLTST(I,J),J=1,2),I=1,5
38 1000 FORMAT(5I4)
39 C READ ** IN THE CRITICAL PLANTING DAYS
40 READ(5,1000)IPLTY
41 1000 FORMAT(I8)
42 C READ ** IN THE WORKING TIME STRATEGY MAX OF 6 SETS OF (JUL.DAY HR/DAY
READ(5,1000)((IHRPDY(I,J),J=1,2),I=1,6)
C READ ** IN THE LAST POSSIBLE DAY TO BEGIN HARVEST REGARDLESS OF GRAIN
C MOISTURE IN FIELD
READ(5,1000)IHRDY
C READ ** IN THE GRAIN MOISTURE THAT STARTS HARVEST
READ(5,1005)HARMST
C READ ** IN THE FIRST AND LAST MODELING YEAR (2 DIGITS ONLY)
READ(5,1000)IYRSTR,IYRSTP
C READ ** IN PLANTING RATE(AC/HR).TWO HARVEST RATES(AC/HR,BU/HR)
READ(5,1005)PLTRAT,HARRAT
1005 FORMAT(10F5.0)
C READ ** IN PRINT AND PUNCH CONTROL VALUES
READ(5,1000)IPRINT,IPUNCH
CALL SIMYRS
STOP
END
SUBROUTINE SIMYRS
COMMON/GROW1/(IFLD(30,6),IPLTST(5,2),JPLTST(5,2),IPLTDY(4),IHRPDY(6,2),IDAY(3),
2 IHARDY,ISLKDY(3),IYRSTR,IYRSTP,MINFLD,IPRINT,IPUNCH)
COMMON/GROW2/(RFLO(30,7),S1FLD(30),I2FL0(30),S3FLD(30),S4FLD(30),
2 YLDPT(D,3),YLDPLT(3,3),YLDHAR(2),ACPLT(5),
3 VTYG0U(3),DOMST(5),ODCCEF(5,3),HARLOT(18,50,4),HARMST,
4 PLTRAT,HARRAT(I2).FRZMST,FR2DMG,PLTACR,HARACR,HARBUL
IF(IYRSTR.LT.58)STOP 1
IF(IYRSTR.GT.75)STOP 2
IF(IYRSTP.LT.58)STOP 3
IF(IYRSTP.GT.75)STOP 4
IF(IYRSTP.LT.IYRSTR)STOP 5
WRITE(6,200)IYRSTR,IYRSTP
200 FORMAT(/' SIMULATED CORN PRODUCTION FOR A TYPICAL CENTRAL IOWA')
* FARM/** STARTING WITH THE 19',12,' PRODUCTION SEASON/**
* FINISHING WITH THE 19',12,' PRODUCTION SEASON*)
WRITE(6,201)IPLTDY
201 FORMAT(/' OF FIRST ALLOWABLE JULIAN DAY TO BEGIN PLANTING - ',14/
* OLAST JULIAN DAY TO PLANT FULL SEASON CORN -',14/
* OLAST JULIAN DAY TO PLANT MEDIUM SEASON CORN -',14/
* OLAST JULIAN DAY TO PLANT SHORT SEASON CORN -',14/
WRITE(6,202)MINFLD
202 FORMAT(/' A MINIMUM OF ',13,' GOOD SPRING FIELD DAYS MUST OCCUR ',
* BEFORE PLANTING CAN BEGIN')
WRITE(6,203)PLTRAT
203 FORMAT(/' PLANTING RATE IS ',F5.2,' ACRES PER HOUR/')
WRITE(6,204)((JPLTST(I,J),J=1,2),I=1,5)
204 FORMAT(' PLANTING STRATEGY/* NO. AC. VARIETY*/5(' ',16,4X,13/)
WRITE(6,205)((IHRPDY(I,J),J=1,2),I=1,6)
205 FORMAT(/' TIME AVAILABLE FOR FIELD OPERATIONS/*
* JULIAN DATE HOURS PER DAY*/
* 6(' ',5X,14,19X,12/)
WRITE(6,206)HARMST,IHRDY
206 FORMAT(/' HARVEST WILL BEGIN WHEN THE CORN DRIES DOWN TO ',F4.1,
* PERCENT MCWB/* HARVEST WILL BEGIN REGARDLESS OF MOISTURE ',
* ON JULIAN DATE ',13,' /*
WRITE(6,207)HARRAT
207 FORMAT(10F5.0)
207 FORMAT('HARVEST RATE IS THE LESSER OF '.F5.2,' ACRES PER ',F6.2,' BUSHELS PER HOUR.')
208 FORMAT('OUTPUT OPTIONS IN EFFECT'/
    'IPRINT =',I2,' IPUNCH =',I2)
100 CONTINUE
    IN=IN+1
    DO 10 I=1,2
    DO 10 J=1,5
    10 IPLST(J,I)=JPLTST(J,I)
    DO 20 J=1,30
    20 IFLD(J,4)=0
    DO 500 1=1,5
    ACPLT(1)=FLOAT(IPLTST(C.1))
    500 CONTINUE
    IPLANT=1.
    IYIELD=IN-7
    ISILK =1.
    IF(IHRPDY(I,1).EQ.0)STOP 6
    IDOE=0
    IDRY=0
    IHAR=0
    IYRMOD=IN+50
    IF(IPRINT.GE.1)WRITE(6.1012)IYRMOD
    IFLD=0
    IHRL0T=0
    HARBUR=0.0
    HARACR=0.0
    PLTACR=0.0
    1012 FORMAT('1'/','20X,'PRODUCTION SEASON'//)
    IWRKDY=0
    IF(IPRINT.GE.2)WRITE(6.1013)
    1013 FORMAT('0',20X,'DATE VS GRAIN MOISTURE TABLE'//' DATE/PLACE20X,',**1 - 30 FIELDS'//)
    JULDAY=91
    REWIND IN
    102 CONTINUE
    DO 505 1=1,6
    IF(IHRPDY(I,1).EQ.0) GO TO 510
    IF(JULDAY.GE.IHRPDY(I,1))WRKHRS=FLOAT(IHRPDY(I,2))
    505 CONTINUE
    510 CONTINUE
    READ(IN,1015)IDAY,DB,DP,WB,WBPDRS,RH,ABSHUM,SPCVOL,IFREZ,IGO,EQM,
    *GDU,CUMGDU
    1015 FORMAT(3A4,5F6.1,F8.6,F6.2,2I3,F6.4,F6.2,F6.0)
    IWRKDY=IWRKDY+IGO
    IF(IWRKDY.LE.MINFLD) GO TO 700
    IF(JULDAY.LE.IPLTDY(I)) GO TO 700
    IF(IPLANT.EQ.0) GC TO 525
    IF(JULDAY.GT.IPLTDY(4)) GO TO 700
    DD 515 I=1,5
    IST=I
    IF(ACPLT(1).NE.0) GO TO 520
515 CONTINUE  
IPLANT=0  
GO TO 525  
520 IF(IGO.EQ.0) GO TO 525  
CALL PLANT(JULDAY,WRKhrs,IST,IYIELD,IPFLD,CUMGOU)  
IF(IPFLD.GT.30)IPFLD=30  
525 CONTINUE  
IF(JULDAY.LT.150) GO TO 540  
IF(ISILK.EQ.0) GO TO 540  
ISILK=0  
DO 535 J=1,IPFLD  
IF(IFLD(J).LT.2)ISILK=1  
IF(IFLD(J).EQ.1.AND.CUMGOU.GE.S1FLD(J))GO TO 530  
GO TO 535  
530 IFLD(J,J)=JULDAY  
IFL(J,J)= JULDAY+ISLKOY(I)FLDC(J)  
IOY=1  
535 CONTINUE  
540 CONTINUE  
IF(IOY.EQ.0) GO TO 555  
IOY=0  
DD 550 K=1,IPFLD  
IF(IFLD(K).LT.3)IOY=1  
IF(IFLD(K).EQ.JULDAY) GO TO 545  
GO TO 550  
545 IFLD(K,J)=3  
S3FLD(K)=DDMST(1)  
IOY=1  
550 CONTINUE  
555 CONTINUE  
IF(IOY.EQ.0) GO TO 560  
CALL FLODry(DB,WSBPRS,IIHAR,JULDAY,EOH,IPFLD)  
560 CONTINUE  
IF(IFRZ.EQ.1.AND.JULDAY.GT.220) CALL FREEZE(IFRZCT,IPFLD)  
563 IF(IHAR.EQ.0.OR.IGO.EQ.0) GO TO 700  
CALL HAV(IIHAR,JULDAY,WRKhrs,IPFLD,IMHLOT,IYIELD,IOY,IIHAR)  
700 JULDAY=JULDAY+1  
IF(JULDAY.EQ.366)REWIND IN  
IF(JULDAY.EQ.366)CALL PRINT1(IYRMQD,IPFLD,IMHLOT,IYIELD)  
IF(IYRMQD.EQ.IYRSTP.AND.JULDAY.EQ.366) CALL PRINT2  
IF(JULDAY.EQ.366) GO TO 100  
GO TO 102  
END  
SUBROUTINE PLANT(JULDAY,WRKhrs,IST,IYIELD,IPFLD,CUMGOU)  
COMMON/GROW1/  
1 IFLD(30,6),IPLTST(5,2),JPLTST(5,2),IPLTDY(4),IHARPDY(6,2),IYD(3),  
2 IHAR,YLSPD(10,3),YLSPLOT(3,3),YLDMAR(2),YLDCOM(2),ACPLT(5),  
3 VTYGOU(3),DDMST(5),ODDCOF(5,3),HARLOT(18,50,4),HARMST,  
4 PNTMAT,HARRAT(2),FRZMST,FRZDGM,PLTACR,HARACR,HARBUL  
INTEGER PFLD  
COMMON/GROW2/  
1 RFLD(30,7),S1FLD(30),S2FLD(30),S3FLD(30),S4FLD(30),  
2 VYOPT(10,3),VYDPLT(3,3),VYDMAR(2),YLDCOM(2),ACPLT(5),  
3 VTYGOU(3),DDMST(5),ODDCOF(5,3),HARLOT(18,50,4),HARMST,  
4 PNTMAT,HARRAT(2),FRZMST,FRZDGM,PLTACR,HARACR,HARBUL  
INTEGER PFLD
TIME=WRKHRS
ACRES=PLTRAT*TIME
IF(ACPLT(IST).LE.0.0)RETURN
IF(ACRES.GT.ACPLT(IST))GO TO 200
ACPLT(IST)=ACPLT(IST)-ACRES
TIME=0.0
100 PFLD=PFLD+1
IF(PFLD.GT.30)RETURN
IFLD(PFLD,1)=1
IFLD(PFLD,2)=JULDAY
IF(JULDAY.GT.145)GO TO 120
IF((JULDAY.GT.135)AND.IPLTST(IST,2).EQ.1)IPLTST(IST,2)=2
IF((JULDAY.GT.135)AND.IPLTST(IST,2).EQ.3)IPLTST(IST,2)=3
SIFLD(PFLD)=CUMGDU+VTYGDU(IPLTST(IST,2))
S4FLD(PFLD)=ACRES
RFLD(PFLD,1)=ACRES
RFLD(PFLD,2)=YLDPOT(IYIELD,IFLD(PFLD,6))
IF((JULDAY.GT.135))GO TO 110
RFLD(PFLD,3)=0.0
GO TO 500
110 IF((JULDAY.GT.135))GO TO 120
RFLD(PFLD,3)=0.0
IF((IFLD(PFLD,6).EQ.1)RFLD(PFLD,3)=YLDPLT(1,1)*(JULDAY-125)
GO TO 500
120 IF((JULDAY.GT.145))GO TO 130
AA=YLDPLT(1,1)*10.
RFLD(PFLD,3)=AA*(YLDPLT(1,2)*(JULDAY-125))
IF((IFLD(PFLD,6).EQ.2)RFLD(PFLD,3)=BB+YLDPLT(2,2)*(JULDAY-135)
IF((IFLD(PFLD,6).EQ.3)RFLD(PFLD,3)=CC+YLDPLT(3,2)*(JULDAY-135)
GO TO 500
130 IF((IFLD(PFLD,6).EQ.1)RFLD(PFLD,3)=YLDPLT(1,1)*(JULDAY-145)
*+AA +YLDPLT(1,2)*10.
BB=YLDPLT(2,2)*10.
CC=YLDPLT(3,2)*10.
IF((IFLD(PFLD,6).EQ.2)RFLD(PFLD,3)=BB+YLDPLT(2,3)*(JULDAY-145)
IF((IFLD(PFLD,6).EQ.3)RFLD(PFLD,3)=CC+YLDPLT(3,3)*(JULDAY-145)
500 PLTACR=PLTACR+ACRES
IF((TIME.EQ.0.0))RETURN
IST=IST+1
IF((IST.GT.5))RETURN
GO TO 40
200 ACRES=ACPLT(IST)
RUSE=ACPLT(IST)/PLTRAT
TIME=TIME-RUSE
ACPLT(IST)=0.0
GO TO 100
END
SUBROUTINE FLDDRY(DB,WBDPRS,IHAR,JULDAY,EQM,IPFLD)
COMMON/GROW1/ 267.
1 IFLD(30,6),IPLTST(5,2),JPLTST(5,2),IPLTIDY(4),IHARPDY(6,2),IDAY(3), 268.
2 IHARDY,ISLKDY(3),IVSTR,IVRSTP,MINFLD,IPRINT,IPUNCH 269.
COMMON/GROW2/ 270.
1 RFLD(30,7),S1FLD(30),S2FLD(30),S3FLD(30),S4FLD(30), 271.
2 YLDPOT(18,3),YLDPLT(3,3),YLDHAR(2),YLDCOM(2),ACPLT(5), 272.
3 VTYGOU(3),DDMST(5),DDCOEF(5,3),HARLOT(18,50,4),HARMST, 273.
PLTRAT, HARRAT(2), FRZMST, FRZDMG, PLTACR, HARACR, HARBUL

EQM = EQM * 100.
IF (EQM > 30.) EQM = 30.
DO 565 L = 1, IFLD
K = IFLD(L, 1)
KD = K - 2
IF (K > LT, 3) GO TO 565
IF (K > EQ, 4) GO TO 560
IF (K > EQ, 5) GO TO 566
IF (S3FLD(L) > LT, FRZMST, AND, IFLD(L, 4) = EQ) IFLD(L, 4) = JULDAY
IF (K > GT, 4) GO TO 558
RDMST = DDCOEF(KD, 1) * (DDCOEF(KD, 2) * DDCOEF(KD, 3) * DB)
S3FLD(L) = S3FLD(L) - RDMST
IF (S3FLD(L) < 0) RDMST = 0
RDMST = DDCOEF(KD, 1) * (S3FLD(L) - (EQM - DDCOEF(KD, 2)))
RFLD(L, 4) = BUSBAM
PERDAM = FRZDMG * (S3FLD(L) - FRZMST)
BUSDAM = PERDAM * 0.01 * (RFLD(I, 2) - RFLD(I, 3))
RFLD(I, 4) = BUSDAM
CONTINUE

SUBROUTINE FREEZE(IFRZCT, IFLD)
COMMON/GROW1/ IFLD(30, 6), IPLTST(5, 2), JPLTST(5, 2), IPTLDY(4), IHPRDY(6, 2), IDAY(3),
IHARDY, ISLKDY(3), IYRSTR, IYRSTP, MINFOFLD, IPRINT, IPUNCH
COMMON/GROW2/ RFLD(30, 7), S1FLD(30), S2FLD(30), S3FLD(30), S4FLD(30),
YLDPDT(18, 3), YLDPLT(3, 3), YLDMAR(4, 2), YLDCCD(2), ACPLT(5),
VTYGD(3), DDMST(3), DDCOEF(5, 3), HARLOT(18, 50, 4), HARMST,
PLTRAT, HARRAT(2), FRZMST, FRZDMG, PLTACR, HARACR, HARBUL
INTEGER IPZDAM(30)
IF (IPRINT.EQ.2) WRITE (6, 1000) IDAY, IDAY, IDAY
100 FORMAT(3A4, 30F4.0)
RETURN
END

SUBROUTINE FREEZE(IFRZCT, IFLD)
COMMON/GROW1/ IFLD(30, 6), IPLTST(5, 2), JPLTST(5, 2), IPTLDY(4), IHPRDY(6, 2), IDAY(3),
IHARDY, ISLKDY(3), IYRSTR, IYRSTP, MINFOFLD, IPRINT, IPUNCH
COMMON/GROW2/ RFLD(30, 7), S1FLD(30), S2FLD(30), S3FLD(30), S4FLD(30),
YLDPDT(18, 3), YLDPLT(3, 3), YLDMAR(4, 2), YLDCCD(2), ACPLT(5),
VTYGD(3), DDMST(3), DDCOEF(5, 3), HARLOT(18, 50, 4), HARMST,
PLTRAT, HARRAT(2), FRZMST, FRZDMG, PLTACR, HARACR, HARBUL
INTEGER IPZDAM(30)
IF (IPRINT.EQ.2) WRITE (6, 1000) IDAY, IDAY, IDAY
IFRZCT = 1
100 FORMAT(3A4, 30F4.0)
FREEZE **** ** *, '3A4,' *, '3A4,' ** ****
FREEZE DAMAGE ARRAY = ', '3A4,' *, '3A4,' ** ****
DO 100 I = 1, IFLD
IFZDAM(I) = 0
IF (S3FLD(I) = LT, FRZMST) GO TO 100
IFZDAM(I) = 1
PERDAM = FRZDMG * S3FLD(I) - FRZMST
BUSDAM = PERDAM * 0.01 * (RFLD(I, 2) - RFLD(I, 3))
RFLD(I, 4) = BUSDAM
CONTINUE

CONTINUE
IF( IPRINT.EQ.2) WRITE(6,1010) IFZDAM(I),I=1,IPFLD)
RETURN
END
SUBROUTINE HARV(DB,JULDAY,WRKHRS,IPFLD, IYIELD, IDRY, IHAR)
COMMON/GROW1/  
1 IFLD(30,6),IPLTST(5,2),JPLTST(5,2),IPLTSTY(4), IHARDY(6,2), IDAY(3),
2 IYRSTR*1YRSTP, MINFLD, IPRINT, IPUNCH
COMMON/GROW2/  
1 RFLD(30,7), S1FLD(30), S2FLD(30), S3FLD(30), S4FLD(30).
2 YLDPLT(18,3),YLDP0T(18,3),YLDHAR(2), YLDCOM(2), ACPLT(5),
3 VTGYOU(3), DDOMST(5), CDCOEF(5,3), HARMAT(18,50,4), HARMST,
4 PLTRAT, HARRAT(2), FRZMST, FRZDMG, PLTACR, HARCRR, HRBUR

TIME=WRKHRS
10 IDRY=0
IHAR=0
IPKFLD=0
HRMSDY=HARMST
IF(JULDAY.GT.IHARDY) HRMSDY=DOMST(3)
DO 100 I=1,IPFLD
IF(IFLD(I,1).GT.7) GO TO 100
IDRY=1
IHAR=1
IF(S3FLD(I,LT,HRMSDY) IPKFLD=I
IF(S3FLD(I,LT,HRMSDY) HRMSDY=S3FLD(I)
100 CONTINUE
IF(IPKFLD.EQ.0) RETURN
IHRLOT=IHRLOT+1
C CALCULATE HARVESTED YIELD, FIELD LOSSES, AND MOISTURE
COMLOS=YLDCOM(1)
IF(JULDAY.GE.320) COMLOS=YLDCGM(2)
FLDLOS=0.0
IF(JULDAY.GE.325) FLDLOS=YLDHAR(1)*(JULDAY-274)
IF(JULDAY.GE.320) FLDLOS=YLDHAR(1)* (319-274)+YLDHAR(2)*
* (JULDAY-319)
RFLD(IPKFLD,5)=COMLOS+FLDLOS
RFLD(IPKFLD,6)=RFLD(IPKFLD,2)-RFLD(IPKFLD,3)-RFLD(IPKFLD,4)
RFLD(IPKFLD,7)=S3FLD(IPKFLD)
IFLD(IPKFLD,5)=JULDAY
HARRT1=HARRAT(2)/RFLD(IPKFLD,6)
HVRAT=HARRAT(1)
IF(HARRT1.LT.HVRAT) HVRAT=HARRT1
ACRES =HVRAT* TIME
ACRES2=S4FLD(IPKFLD)
IF(ACRES.LT.ACRES2) GO TO 110
IFLD(IPKFLD,1)=8
HRUSED= ACRES2/HARRT1
TIME = TIME - HRUSED
ACRES = ACRES2
S3FLD(IPKFLD)=0.0
GO TO 115
110 TIME=0.0
115 CONTINUE
BUSHEL=ACRES*RFLD(IPKFLD,6)
HARLOT(IYIELD, IYIELD,1) = JULDAY
RETURN
END
HARLOT(IYIELD, IHRLOT, 2) = BUSHEL
HARLOT(IYIELD, IHRLOT, 3) = RFLD(IPKFLD, 7)
HARLOT(IYIELD, IHRLOT, 4) = DB
S4FLD(IPKFLD) = S4FLD(IPKFLD) - ACRES
HARBL = HARBL + BUSHEL
HARACR = HARACR + ACRES
IF (TIME.EQ.0.0) RETURN
GO TO 10
END

SUBROUTINE PRINT1(IYRMOD, IPFLD, IHRLOT, IYIELD)
COMM/GROW1/
1 IFLD(30, 6), IPILOTST(5, 2), JPLTST(5, 2), IPILOYD, IHRPBY(6, 2), IDAY(3),
2 IHRDY, IYLDKD(3), IYRSTR, IYRSTP, MINFLD, IPRINT, IPRINT
COMMON/GROW2/
1 RFLD(30, 7), S1FLD(30), S2FLD(30), S3FLD(30), S4FLD(30),
2 YLDPT(18, 3), YLDPDD(18, 3), YLDHAR(2), YLDCOM(2), ACPLT(5),
3 YLDGD(3), YLDDMST(5), YLDGD(3), HARLOT(18, 50), HARST,
4 PLTRAT, HARRAT(2), FRZMDG, PTACR, HARCR, HARBL
INTEGER IVAR(3)
DATA IVAR("FULL", "MED", "SHRT")
IF (IPRINT.EQ.0.0) RETURN
WRITE(6, 1000) PLTACR, HARACR, HARBL
FORMAT(0*, 'ACRES PLANTED = ', F9.1)
* 0*, 'ACRES HARVESTED = ', F9.1
* 0*, 'BUSHELS HARVESTED = ', F9.1)
IF (IPRINT.GE.1) GO TO 100
RETURN
100 DO 150 I = 1, IPFLD
WRITE(6, 1002) IYRMOD, I, IVAR(IFLD(I, 6))
COMM/GROW2/
1 RFLD(30, 7), S1FLD(30), S2FLD(30), S3FLD(30), S4FLD(30),
2 YLDPT(18, 3), YLDPDD(18, 3), YLDHAR(2), YLDCOM(2), ACPLT(5),
3 YLDGD(3), YLDDMST(5), YLDGD(3), HARLOT(18, 50), HARST,
4 PLTRAT, HARRAT(2), FRZMDG, PTACR, HARCR, HARBL
INTEGER IVAR(3)
DATA IVAR("FULL", "MED", "SHRT")
IF (IPRINT.EQ.0.0) RETURN
WRITE(6, 1000) PLTACR, HARACR, HARBL
FORMAT(0*, 'ACRES PLANTED = ', F9.1)
* 0*, 'ACRES HARVESTED = ', F9.1
* 0*, 'BUSHELS HARVESTED = ', F9.1)
IF (IPRINT.GE.1) GO TO 100
RETURN
100 DO 150 I = 1, IPFLD
WRITE(6, 1002) IYRMOD, I, IVAR(IFLD(I, 6))
COMM/GROW2/
1 RFLD(30, 7), S1FLD(30), S2FLD(30), S3FLD(30), S4FLD(30),
2 YLDPT(18, 3), YLDPDD(18, 3), YLDHAR(2), YLDCOM(2), ACPLT(5),
3 YLDGD(3), YLDDMST(5), YLDGD(3), HARLOT(18, 50), HARST,
4 PLTRAT, HARRAT(2), FRZMDG, PTACR, HARCR, HARBL
INTEGER IVAR(3)
DATA IVAR("FULL", "MED", "SHRT")
IF (IPRINT.EQ.0.0) RETURN
WRITE(6, 1000) PLTACR, HARACR, HARBL
FORMAT(0*, 'ACRES PLANTED = ', F9.1)
* 0*, 'ACRES HARVESTED = ', F9.1
* 0*, 'BUSHELS HARVESTED = ', F9.1)
IF (IPRINT.GE.1) GO TO 100
RETURN
100 DO 150 I = 1, IPFLD
WRITE(6, 1002) IYRMOD, I, IVAR(IFLD(I, 6))
COMM/GROW2/
1 RFLD(30, 7), S1FLD(30), S2FLD(30), S3FLD(30), S4FLD(30),
2 YLDPT(18, 3), YLDPDD(18, 3), YLDHAR(2), YLDCOM(2), ACPLT(5),
3 YLDGD(3), YLDDMST(5), YLDGD(3), HARLOT(18, 50), HARST,
4 PLTRAT, HARRAT(2), FRZMDG, PTACR, HARCR, HARBL
INTEGER IVAR(3)
DATA IVAR("FULL", "MED", "SHRT")
IF (IPRINT.EQ.0.0) RETURN
WRITE(6, 1000) PLTACR, HARACR, HARBL
FORMAT(0*, 'ACRES PLANTED = ', F9.1)
* 0*, 'ACRES HARVESTED = ', F9.1
* 0*, 'BUSHELS HARVESTED = ', F9.1)
IF (IPRINT.GE.1) GO TO 100
RETURN
100 DO 150 I = 1, IPFLD
WRITE(6, 1002) IYRMOD, I, IVAR(IFLD(I, 6))
COMM/GROW2/
1 RFLD(30, 7), S1FLD(30), S2FLD(30), S3FLD(30), S4FLD(30),
2 YLDPT(18, 3), YLDPDD(18, 3), YLDHAR(2), YLDCOM(2), ACPLT(5),
3 YLDGD(3), YLDDMST(5), YLDGD(3), HARLOT(18, 50), HARST,
1000 FORMAT(//** HARVESTED GRAIN FLOW FOR THE 19th, 12th, 3rd Crop Season**//)
   * JULIAN DATE BUSHELS MOISTURE TEMPERATURE**/)
   IST=IYRSTR-57
   ISP=IYRSTR-57
   DO 100 I=IST,ISP
   WRITE(6,1000)IYRMOD
   JYRMOD=IYRMOD
   IYRMOD=IYRMOD+1
   DO 200 J=1,50
   IF(HARLOT(I,J,1).EQ.0.0) GO TO 100
   IF(PRINT.GE.1) WRITE(6,1002)(HARLOT(I,J,K),K=1,4)
   200 IF(IPUNCH.GE.1) WRITE(7,1003)JYRMOD,(HARLOT(I,J,K),K=1,4)
   100 CONTINUE

1002 FORMAT(' I,F10.0,F10.1')
1003 FORMAT(15,I10.2)
STOP 999
END

//GO*FT08F001 DD DSN=V.U3383.DATA58,DISP=SHR,DCB=BUFNO=1
//GO*FT09F001 DD DSN=V.U3383.DATA59,DISP=SHR,DCB=BUFNO=1
//GO*FT10F001 DD DSN=V.U3383.DATA60,DISP=SHR,DCB=BUFNO=1
//GO*FT11F001 DD DSN=V.U3383.DATA61,DISP=SHR,DCB=BUFNO=1
//GO*FT12F001 DD DSN=V.U3383.DATA62,DISP=SHR,DCB=BUFNO=1
//GO*FT13F001 DD DSN=V.U3383.DATA63,DISP=SHR,DCB=BUFNO=1
//GO*FT14F001 DD DSN=V.U3383.DATA64,DISP=SHR,DCB=BUFNO=1
//GO*FT15F001 DD DSN=V.U3383.DATA65,DISP=SHR,DCB=BUFNO=1
//GO*FT16F001 DD DSN=V.U3383.DATA66,DISP=SHR,DCB=BUFNO=1
//GO*FT17F001 DD DSN=V.U3383.DATA67,DISP=SHR,DCB=BUFNO=1
//GO*FT18F001 DD DSN=V.U3383.DATA68,DISP=SHR,DCB=BUFNO=1
//GO*FT19F001 DD DSN=V.U3383.DATA69,DISP=SHR,DCB=BUFNO=1
//GO*FT20F001 DD DSN=V.U3383.DATA70,DISP=SHR,DCB=BUFNO=1
//GO*FT21F001 DD DSN=V.U3383.DATA71,DISP=SHR,DCB=BUFNO=1
//GO*FT22F001 DD DSN=V.U3383.DATA72,DISP=SHR,DCB=BUFNO=1
//GO*FT23F001 DD DSN=V.U3383.DATA73,DISP=SHR,DCB=BUFNO=1
//GO*FT24F001 DD DSN=V.U3383.DATA74,DISP=SHR,DCB=BUFNO=1
//GO*FT25F001 DD DSN=V.U3383.DATA75,DISP=SHR,DCB=BUFNO=1
//GO*SYSIN DD *
15
300 1
116 136 148 155
92 7 121 8 135 9 170 8
305
24
68 68
5 2.5 300
2 0
SECTION II:
FALDRA - A MODEL FOR
LOW-TEMPERATURE CORN DRYING SYSTEMS
INTRODUCTION

Most low-temperature drying models are designed to simulate the drying of a "unit" (column) of grain. Inputs typically include airflow and grain quantity in the generalized units of cubic feet of air per minute per bushel and fractions of a full bin. FALDRY is unique because it was designed to simulate the performance of a complete farm system for low-temperature drying. FADRY was developed with the following objectives in mind:

- Simulate a complete system of one to six low-temperature drying bins for each crop season using 24-hour average weather data.
- Allow total layer-filling flexibility by enabling each bin to accept any specified quantity of grain on a daily basis.
- Determine the air delivery rate and the resultant heat rise of the air based on fan and bin specifications and daily quantity of grain in the bin.
- Predict the grain moisture profile even at the high airflow rates associated with layer filling.
- Predict drying time and electricity usage.
- Simulate a complete drying season using 3-5 CPU seconds per bin.

FALDRY is a user-oriented computer model. Both the input and output (I/O) forms of FALDRY are designed to be easily understood by the researcher, designer, student, and farm manager alike. All I/O specifications of drying equipment and grain are expressed in "common" English units, i.e., fan size - horsepower, bin dimensions - feet, electricity usage - kilowatt-hours, corn quantity - bushels, etc. Thus it is imperative to use the common English units to enhance the reader's ability to understand and use the FALDRY model.

1 bu = 1 bushel of corn = 47.32 pounds of dry matter.
The literature review covers the existing digital low-temperature grain drying models and some of the major advancements that led to their development. General reviews covering the complete spectrum of grain drying models can be found in Brooker et al. (1974), Bakker-Arkema et al. (1978), and Morey et al. (1978a).

Between 1920 and 1965 several authors published mathematical models to predict the heat and/or moisture transfer in beds of small grains. One of the most noteworthy works on the modeling of deep-bed grain drying was reported by Hukill (1947). Assuming a unique relationship between the rate of moisture loss and the temperature gradient in a bed of grain, Hukill (1954) developed an equation and a series of dimensionless curves to predict grain moisture at any depth in the bed after a specified drying time. Even though more sophisticated simulation techniques presently exist, Hukill's approach is useful because of its simplicity and rapid calculation speed. A modification of Hukill's method is presently used and commonly referred to as the logarithmic model.

Boyce (1965) published the first modern study of deep bed drying using a digital computer model. The model was semiempirical. Its results did not agree well with experimental observations. A year later Boyce (1966) published a more theoretical model that was based on the laws of heat and mass transfer. It was an improved model, but lacked data for the basic parameters of equilibrium moisture content and convective heat transfer.
An important series of semiempirical models for fixed-bed, concurrent-, cross- and counterflow grain dryers was proposed by Thompson (1967). This was followed by a number of papers on the drying model (Thompson et al., 1968), a comparison of continuous-flow dryers (Thompson et al., 1969), and the optimal-dryer design (Thompson, 1970). In contrast to Thompson's models which were based on a semiempirical, thin-layer drying equation, the concurrent development of the Michigan State University (MSU) models were based on theoretical analysis of the heat and mass transfer leading to a set of partial differential equations. These equations were then solved by using time-consuming numerical methods. A complete report of the MSU models was published by Bakker-Arkema et al., (1974).

Renewed interest developed in low-temperature grain drying during the late sixties. Some of the first reported studies came from Purdue University in Indiana. Using the low-temperature, thin-layer drying equation proposed by Sabbah (1968) and the deep-bed drying model of Thompson et al. (1968), Flood et al., (1969) developed a natural-air corn drying model. The model also predicted the amount of grain deterioration based on data published by Saul (1967). Using layer thicknesses of one inch and time increments of one hour, the model produced acceptable results. Subsequent use of the model reported by Morey and Peart (1969), illustrates the usefulness of simulation models for optimization studies.

Low-temperature drying studies were also conducted at three other locations (Illinois, Ohio, and Nebraska) during this same time period. Hamdy and Barre (1970) and Barre and Hamdy (1971), Barre et al. (1971)
reported the further development and application of Hukill's (1954) logarithmic model. This Ohio study was unique because the simulation model was developed and run on a hybrid computer. The Nebraska study reported on the simulated and experimental results of both refrigerated and natural air high moisture corn storage systems. The model used by Thompson et al., (1971) was similar to his original deep-bed model with a modified thin-layer equation and incorporated the effect of grain deterioration as reported by Steele et al., (1969). The Illinois model developed and used by Bloome and Shove (1971, 1972) was unique in its simplicity. By assuming near equilibrium conditions between the drying air and grain mass at each layer, it could successfully simulate low-temperature drying systems without using drying equations. The key elements of the model were the psychrometric properties of air, an equilibrium moisture content equation and the specific heat of corn.

A significantly improved equilibrium model was published by Thompson (1972). A sophisticated solution algorithm enabled the model to compute precise equilibrium conditions for both drying and rewetting situations. The model incorporated the updated deterioration equation reported by Saul (1970). The "Thompson Storage Model" predicts changes in grain moisture, temperature, and dry matter decomposition resulting from respiration within the grain, heat transferred through the bin walls, and conditioning of the grain by continuous aeration.

Beginning in 1974, the federal government funded research to study the feasibility of using solar energy as a supplemental heat source for low-temperature corn drying. Three different simulation models were
used to test the hypothesis for several locations throughout the corn belt. The use of the "Thompson Storage Model" was reported by Pierce and Thompson (1976). The use of a significantly modified "MSU Deep Bed Model" was reported by Bakker-Arkema et al. (1977). The modifications were necessary because the execution time of the original model increased drastically as the airflow decreased and drying time increased and the original model contained no provisions for simulating condensation and rewetting. The results from the modified version agreed well with the original model and experimental observations, but when compared with the "Thompson Storage Model" it used an excessive amount of computer time. The development and use of a third model was reported by Morey et al. (1976, 1977). The "Morey Model" is a modified version of the "Thompson Storage Model" and has several advantages over other low-temperature corn drying models:

1. It executes as fast as the "Thompson Storage Model", i.e., 3-5 CPU-seconds for 1000 hours of fan operation using 24-hour time increments.

2. In addition to being an "equilibrium" model it incorporates the Sabbah thin-layer drying equation. Thus it is capable of predicting the drying profile for higher airflow and dynamic weather conditions typical of the corn-belt in the fall.

3. It has received intensive validation against actual field observations.

4. The FORTRAN code is clearly written and contains good internal documentation.
More recently, the development of additional low-temperature drying models for corn and small grains have been reported by Pfost et al. (1977), Sabbah et al. (1977), and Pierce and Thompson (1978). Basically the models are of one or a combination of the previously described types.

It is important to note that at the heart of a low-temperature corn drying model are mathematical expressions of the grain properties and the psychrometric properties of air. The three major sources of this information are as follows:

2. The Psychrometric Properties of Air (Brooker et al., 1974).
3. The Equilibrium Moisture Content of Grain (Pfost et al., 1976).
SELECTION OF A BASIC DRYING MODEL

During the last few years, several of the existing corn drying models have been run on the digital IBM compatible computers at Iowa State University; including the Thompson High Temperature Models, the MSU Models, the Thompson Storage Model, and the Morey Model. Only the Thompson Storage Model and the Morey Model achieved both the execution speed and moisture prediction accuracy needed for FALDRY. Many computer runs were made comparing the results of the original and modified versions of the two models. Also, several test runs were made comparing the effects of:

1. Using different equilibrium moisture equations with and without the effects of hysteresis.
2. Using 3-hour versus 24-hour weather data.
3. Accounting for, or ignoring, the products of deterioration (CO$_2$, water, and heat) in the drying process.
4. Varying the initial temperature of the corn.
5. Slight changes in average airflow.
6. Slight changes in heat rise across the fan.

Based on these comparisons, personal field experiences, and other published reports, Thompson (1970, 1972), Morey et al. (1976), and Pierce and Thompson (1978), the following comments are made:

1. The pure equilibrium model tends to over predict the rates of both drying and rewetting. This is particularly true near the air entrance and when simulating high airflow rates. Using 24-hour average weather data and assuming some hysteresis in the
equilibrium moisture content of corn tends to reduce this discrepancy but does not alleviate it.

2. The moisture profile predicted by a pure equilibrium model is strictly a function of the computational characteristics of the equilibrium solution algorithm and the number of layers simulated in the model. Judicious selection of approximately 10 simulated layers for a 15-20-foot bed of corn with an airflow rate of approximately 1 cubic foot per minute per bushel just happens to give reasonable correlation to observed moisture profiles. The addition of the Sabbah thin layer drying equations allows the Morey model to realistically predict the moisture profiles of bins with varying depths and airflows. The addition of the Sabbah equation combined with the assumption of equilibrium moisture hysteresis in the Morey model eliminates the tendency to over predict drying and rewetting.

3. Several attempts to simulate the observed results of specific research bins indicate that the equilibrium moisture content of corn may vary slightly depending on hybrid, weather, etc. Simulation results show that slight changes in the equilibrium moisture content of corn (± .5% MCWB) effect both the final moisture content of the grain and the rate of drying front movement. Increasing the equilibrium moisture content assumptions tends to speed the rate of drying front movement. The amount of change is not significant in terms of predicting success or failure of drying but is frustrating when trying to verify the accuracy of the
model against a given set of field observations.

4. Accounting for the water and heat produced by grain respiration and deterioration during the drying process will slightly reduce the predicted drying time and the dry matter loss in the top layer. The amount of change is insignificant as long as the maximum dry matter loss is less than .3%, but in the critical range of 0.5 - 0.7% the reduction in drying time is about 5%. Assuming that the design criteria is 0.5% dry matter loss during the worst year, ignoring the products of deterioration has no significant effect on the predicted results and saves computer time.

5. The equilibrium model is able to simulate the dryeration process. For each 10°F increase in initial grain temperature, about 0.2% MCWB of drying will occur through the entire grain profile during the initial cooling phase. This translates into approximately a 5% reduction in drying time.

6. Airflow rate is extremely critical to the rate of drying. A change in airflow rate will typically result in an equal increase or decrease in drying time. Obviously any increase or decrease in drying time translates into a significant change in dry matter loss.

7. Airflow is critical because the effective airflow in a drying bin is frequently overestimated. There are several reasons that airflow tends to be estimated too high.
   a) Fan curves are developed under ideal conditions.
b) The static head loss in the transition is frequently ignored.

c) Most bins have several significant sources of air leaks
   (i.e., unloading auger tube, entry door joints, lap joints
   around the door frame, base ring, and at the fan transition.)

d) Uneven distribution of sound grain, broken corn, fines, and
   foreign material results in uneven air distribution with
   minimum airflow rates at the most critical locations.

8. It is commonly assumed that the temperature rise across the fan
   is $2^\circ F$, but it is more correct to say that the temperature rise
   ranges from $1-4^\circ F$ depending upon the performance characteristics
   of a specific fan and the static head it operates against. A
   $1^\circ F$ increase in temperature rise will result in about a 5% de­
   crease in drying time. The increase in deterioration rate due
to a small temperature rise is offset by the decrease in drying
time. The net effect is no change in dry matter loss.

The drying algorithm in the "Morey Model" was the best choice for
FALDRY. The model executes with a minimum of CPU time and its results
have been validated against actual field test (Morey et al. (1976). De­
velopment or use of a more sophisticated drying model is probably not
justified. The inherent variability in the properties of corn (equilib­
rrium moisture content and drying rate) and input variables (air tempera­
ture, airflow, grain temperature, and grain moisture) are factors limit­
ing the accuracy of simulating low-temperature drying.
DEVELOPMENT OF FALDRY

General Outline

FALDRY is a deterministic low-temperature grain drying model designed to simulate a system of one to six grain bins with perforated floors and axial-flow fans. Given specifications for bin dimensions, fan and supplemental heater sizes, grain pack factor, and harvest grain flow; FALDRY on a daily basis fills the bins; determines grain depths, airflows, static heads, and temperature rises; and simulates drying. Simulation begins on September 8 and continues for 100 days. FALDRY can accept grain in daily specified quantities and conditions. Based on recommendations by Morey et al. (1978b) and Pfost et al. (1977), FALDRY functions with continuous fan operation (supplemental heat optional). If drying is not completed during the fall season, a fall shutdown criteria is implemented (see Figure 1).

The FALDRY model is a collection of FORTRAN subroutines which together simulate the filling and drying operation. All the major simulation variables (fan and bin specification, weather data, incoming grain flow, output options, etc.) are initialized in the main program and are then transferred through a common statement to the FALDRY subroutines. The subroutine structure makes it easy for FALDRY to be incorporated with corn production and/or harvesting models.

Subroutine FALDRY is the executive program. It initializes internal variables and controls the day-to-day simulation by calling the other major subroutines:
1. The fan starts as soon as the first bushel of corn enters the bin and runs continuously until the user specifies he has finished filling the bin at which time the fall and final shutdown logic takes control. If final shutdown conditions are met before the user indicates that filling is complete, the fan temporarily shuts down until more corn enters the bin.

2. Final shutdown of the fan occurs as soon as the average corn moisture is less than 14.5% MCWB and the maximum corn moisture in all layers is less than 15.5% MCWB, or the date is May 20.

3. If conditions for final shutdown do not occur during the fall drying season, the fall shutdown criteria will turn off the fan and restart it on April 1. Fall shutdown occurs when any one of four conditions are met:
   
   a. The date is after November 15, and the top layer of grain is less than 30°F and less than 18% MCWB.
   
   b. The date is after December 1 and the top layer of grain is less than 25°F and less than 20% MCWB.
   
   c. The date is after December 1 and the top layer of grain is less than 20°F.
   
   d. The date is December 16.

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Winter dry matter deterioration is predicted based on fall shutdown conditions. The effects of winter operation on grain moisture and temperature are not included. Electrical energy for winter aeration is not tabulated.

Figure 1. Fan management strategy for the FALDRY model
1. **FILL**
   Subroutine FILL controls the filling of the bin dependent on the bin dimension and maximum number of layers specified.

2. **FAN**
   Subroutine FAN in conjunction with secondary subroutines VARSEC (Variable Secant Search Technique) and MERIT (Merit Function of the Difference Between Fan Head and Grain Resistance) computes the airflow and heat rise across the axial-flow fan.

3. **PRINT**
   Subroutine PRINT prints on a 1-page format a daily log of the present status of most key variables.

4. **FINPRT**
   Subroutine FINPRT outputs a 1-line printed summary of simulation results. The fall shutdown is printed on I/O unit #1 and the final shutdown is printed on unit I/O #3. Headings for these 1-line summaries must be printed by the main program.

5. **VANCE**
   Subroutine VANCE simulates the actual drying activity; controls the fall and/or final shutdowns; and prints out a one-line summary of shutdown conditions. Subroutine VANCE functions with the aid of several secondary subroutines.

   a. **RHS/PSDP**
      Function RHS in conjunction with function PSDP computes the relative humidity of air given its dry bulb temperature and absolute humidity.
b. ZEROUT
Subroutine ZEROUT is an arithmetic root finding technique that operates on function EQZERO to find the equilibrium point between the wet grain and drying air.

c. Subroutine THLYLT predicts the drying rate of thin layers of corn below 80°F. It is based on the equations developed by Sabbah and Guide.

d. SAFES
Function SAFES is used to predict the amount of dry matter deterioration. It is based on equations developed by Steele and Saul.

Figure 2 illustrates how the FALDRY subroutine package would typically be used.

Implementation of the Morey Model

Most of subroutine VANCE and all of its secondary subroutines are from the original Morey model. In addition to changes in variable names, there were three modifications to the original code:

1. The Morey model could simulate from 1 to 10 layers in the bin.
Layer-filling was possible but only in increments of complete layers. FALDRY allows complete flexibility for layer-filling.
On a daily basis it determines the grain depth and number of layers filled with corn. It computes the percentage of filling

1Significant portions of the FORTRAN code in the Morey model originated in the Thompson Storage Model and the MSU Models.
Figure 2. FALDRY flowchart
for the top layer with grain and simulates a partial layer. Later when filling continues FALDRY completes filling the partial layer and computes a new average moisture content.

2. The maximum number of layers in the bin was increased to 20. This results in increased accuracy when simulating partially-filled bins with high airflows. It reduces the amount of assumed mixing in each layer during the layer filling process. It more precisely defines the position of the initial drying front. These enhancements are important if FALDRY is used to develop an optimum layer filling strategy.

3. The addition of the fan management strategy was outlined in Figure 1.

Development of a Theoretical Fan Model

Low-temperature grain drying systems depend on the drying capacity of ambient air. Fan manufacturers publish the discharge rate versus static head performance of their product line. This information is necessary to design for adequate airflow; but more information is needed to select the optimum fan. To maximize drying efficiency, it is necessary for the fan to deliver as much air as possible with minimum input energy. The key parameter is the delivery rate of air divided by the electrical power requirement (cfm/watt). The effect of varying cfm/watt performance is illustrated in Table 1.

Fan manufacturers rarely publish the actual electrical demands of their products. Thus, it is usually impossible to determine a fan's cfm/watt
Table 1. The effect of fan efficiency

<table>
<thead>
<tr>
<th>Fan performance (cfm/watt)</th>
<th>Drying cost(^a) (c/bu)</th>
<th>Temperature rise(^b) (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td>1.75</td>
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<td>1.7</td>
</tr>
<tr>
<td>1.50</td>
<td>3.2</td>
<td>2.0</td>
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<tr>
<td>1.25</td>
<td>3.8</td>
<td>2.4</td>
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<tr>
<td>1.00</td>
<td>4.8</td>
<td>3.0</td>
</tr>
<tr>
<td>0.75</td>
<td>6.4</td>
<td>4.0</td>
</tr>
<tr>
<td>0.50</td>
<td>9.6</td>
<td>6.0</td>
</tr>
</tbody>
</table>

\(^a\)Assumes drying air conditions of 50°F at 65% RH, 22% MCWB corn dried to an equilibrium moisture of 14.5% MCWB, and electrical energy at 5 cents per kWh.

\(^b\)Assumes the electric motor is positioned in the airstream and all the electrical energy is absorbed by the airstream and dissipated as heat.

Performance curve from manufacturer's literature. The nominal horsepower rating of the fan is a poor indicator of actual power consumption. During actual field tests, a "20 Hp" centrifugal fan consumed approximately 17 kW and a "5-7 Hp" axial fan required about 7.5 kW. From fan performance data supplied by assorted manufacturers, the kilowatt consumption of different fans typically vary from .75 to 1.25 times the nominal horsepower rating while operating in the range of 2-4 inches of water static head. Axial and centrifugal fans vary significantly in performance.

Table 2 tabulates typical performance characteristics of quality axial and centrifugal fans.

Design of an optimum low-temperature drying system is a delicate
Table 2. Fan performance characteristics

<table>
<thead>
<tr>
<th>Static head (inches of water)</th>
<th>Axial fan (cfm/watt)</th>
<th>Centrifugal fan (cfm/watt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.0</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>0.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

balance of conflicting objectives:

1. Design for maximum cfm/watt to decrease drying cost. This is accomplished by selecting the highest efficiency fans and by limiting the static head.

2. Design for maximum airflow to increase drying speed, reduce the probability of failure, and/or allow filling with higher moisture corn.

3. Design for maximum depth. To increase storage capacity and reduce the capital investment.

Careful analysis indicates that the optimum solution may be layer-fill drying with a standard depth bin and high-performance axial fans. This approach offers several advantages.

1. Early in the fall when the ambient air has a high drying potential and layer filling begins, the shallow grain depth allows the axial fans to function at high efficiency thus increasing drying speed and minimizing drying cost.
2. The combination of shallow grain depths and higher fan delivery rates allows harvest to begin earlier at a higher moisture content without risking final grain quality.

3. Beginning harvest earlier in the fall enhances the probability of finishing drying in the fall. This reduces the energy requirement for winter aeration and minimizes management effort.

4. As the harvest season progresses the grain depth increases, the static head increases, the airflow decreases, and the temperature rise across the fan increases to compensate for the increasing relative humidity of the ambient air.

5. With layer filling spread over two to three weeks, starting early in the season with grain near 25% MCWB and finishing with grain at 22% MCWB or less, there is rarely more than 10 feet of wet grain above the drying front at any time and the probability of failure is very low.

FALDRY was specifically designed to test the potential of layer filling for low-temperature drying. Therefore, it assumes the use of an axial fan.

The following equation was developed to predict the delivery rate of typical axial fans.

\[ Q = FHP (1800 - 240 SH) \]

where: \( Q \) = Delivery Rate (cfm)

\( FHP \) = Nominal Fan Size (Hp)

\( SH \) = Static Head (inches of water)

Figure 3 compares the performance curves of several nominal 10 horsepower fans with the predicted performance using equation 1. Equation 1 seems
Figure 3. Fan performance curves for assorted 10 horsepower axial fans
to be quite conservative, but there is another factor to consider. FALDRY assumes that the electric motor in a 10 Hp fan provides exactly 10-brake horsepower to the fan blade and operates with an overall efficiency of 85%, while most commercially available axial fans actually supply significantly more than 10-brake horsepower as measured by electrical power usage. Figure 4 compares cfm/watt performance of the FALDRY fan model with six commercially available axial fans. The FALDRY fan model is a valid approximation of axial fans typically used in farm drying systems.

FALDRY tabulates the cumulative electrical consumption of the fan and optional electric heater. FALDRY computes the power demand of the fan and heater assuming 85% and 100% overall efficiency respectively. FALDRY calculates the temperature rise across the fan and heater by assuming 100% of the electric power is absorbed in the air stream. Ambient air is assumed to have a specific heat of .243 and a specific volume of 12.75 cubic feet per lb of dry air.
Figure 4. Fan performance curves for assorted axial fans
GENERAL

Validation of a simulation model is a sizable task. Due to the interaction of variables like weather, grain properties, and the biological processes of deterioration, complete field validation of models like FALDRY is difficult. But relative limits of model accuracy can be established with suitable laboratory and field testing. Grain drying simulation models can be a good approximation of full-scale grain drying operations.

FALDRY has the advantage that the low temperature drying portion is already an accepted model. Given identical inputs, FALDRY produces the same results as the Minnesota solar model developed by Morey. Thus FALDRY inherits the validation efforts reported by Morey et al. (1976, 1977).

Several comparisons between FALDRY results and field data from the Iowa State University solar grain drying tests have been conducted. Keeping in mind the limitations of the accuracy of input variables, the simulation results closely followed the field data. Allowing a slight modification (+ 1%) of the equilibrium moisture equation from year to year, FALDRY results are within the measurement accuracy of grain moisture meters used on the farm. The instantaneous temperature rise recorded across the fans varied significantly (+ 2°F) but the long-term average was within one-half degree of the values predicted by FALDRY. Two unique validation tests merit detailed description.
Scale Bin Test

During the 1950s and 1960s a major study of unheated air drying and corn deterioration was conducted by the Grain Storage and Conditioning Investigations, Agricultural Research Service, USDA, at Iowa State University. Part of this study was conducted in pilot scale drying bins under laboratory controlled conditions. After the equipment and operating procedures were perfected, Saul (1960) recorded in detail the setup and observations of one set of test runs. One of the reported scale bin tests was selected to be compared with FALDRY results. A description of the laboratory test is as follows:

--14 inch diameter bin within a concentric 30 inch diameter bin

--Twenty 7 1/2 pound layers of 25.1% MCWB corn

--7.2 cfm (3.0 cfm per bu) of 64.6°F air at 75.3% relative humidity

One thermocouple was placed in each layer and the temperature readings were recorded daily. Due to the properties of the specific lot of grain in the test it was necessary to adjust the equilibrium moisture equation in FALDRY by a -1% MCDB. This means that corn which would have originally come to equilibrium at 15% MCWB reached equilibrium at 14.3% MCWB. The heat and water vapor produced by the predicted corn

1The concentric 30-inch diameter bin eliminates heat transfer across the wall of the smaller 14-inch bin.

2During the 456 hours of the test, the dry bulb temperature varied from a low of 64.3 to a high of 65.6 averaging approximately 64.6°F. Likewise the relative humidity averaged 75.3% while varying ± 2%.
deterioration were accounted for in the simulation. Figure 5 shows a comparison of the temperature in each layer as predicted by FALDRY with the laboratory data at drying times of 72 and 360 hours. Table 3 compares the final moisture profile predicted by FALDRY with the laboratory data at the end of the 456-hour test.

Table 3. Final moisture profile for pilot scale bin

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Grain moisture (% MCWB)</th>
<th>Simulated</th>
<th>Observed</th>
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<tr>
<td>20 (top)</td>
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<td>19</td>
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</tr>
<tr>
<td>Average</td>
<td>15.2</td>
<td></td>
<td>15.3</td>
</tr>
</tbody>
</table>
Figure 5. Comparison of results for the pilot scale bins (3.0 cfm/bu)
There was a high correlation between the observed and simulated results. It dramatically illustrates the accuracy of the FALDRY model when supplied with precision inputs recorded under controlled laboratory conditions.

High Airflow Test

The ability of some low-temperature drying models to accurately predict the grain moisture profile at high airflow rates has been doubtful. Since FALDRY was specifically designed to simulate layer-filling systems, it is imperative that it adequately predict moisture profiles for systems with above average airflow. A test was conducted to check for potential problems with high airflow. A description of the test system is as follows:

- 30 feet diameter bin filled with 30 inches of 22% MCWB corn
- One large axial fan delivering 26,000 cfm at 1 inch of water static head

Approximately 1500 bushels of corn were dried with an effective airflow of 17.3 cfm per bushel. The actual airflow was roughly 36 cfm per square foot. The test was conducted on a farm near Pella, Iowa, from 6:00 p.m. September 30 to 3:00 p.m. October 2, 1978. Three-hour recorded weather data from Des Moines, Iowa (30 miles northwest of bin site) was used as input for the FALDRY simulation run. The average dry bulb temperature was 59°F and relative humidity was 75% for the 45-hour test.

Figure 6 compares the field data with the simulated results. A compartmented grain probe and two difference moisture meters were used to determine the corn moisture profile. The FALDRY results were within the
Figure 6. Comparison of results for the high airflow test (17.3 cfm/bu)
accuracy of the moisture meter measurements. Results show that wet grain
(\approx 20\% \text{ MCWB and up}) came to equilibrium with drying air very quickly.
Even near the end of the test when there was 6 inches of grain above 20%
MCWB, sling psychrometer readings above the surface of the grain showed
that the drying air was very near saturation. This test illustrates the
high efficiency potential of low-temperature drying. An average of 443
BTU (0.13 kWh) of electrical energy was used per pound of water removed
from the corn. The final average moisture content in the bin was meas-
ured at 16.6\% MCWB and predicted to be 16.8\% MCWB.
ADDITIONAL USES FOR FALDRY

The FALDRY program is a FORTRAN subroutine package that can be added to an existing computer program. Each subroutine simulates a specific activity or solves a given problem. Individual subroutines can be called by the main program to compute such values as the equilibrium moisture content, allowable storage time, drying rate, and psychrometric properties of air. One particularly interesting study was to determine the performance characteristics of a fan and bin system assuming varying system parameters. The study was conducted using three FALDRY subroutines, FAN (The Axial Fan Model), MERIT (Airflow Resistance in Grain), and VARSEC (A Root Finding Algorithm).

The first step was to specify the "base" bin parameters:

- Bin Diameter: 30 feet$^1$
- Grain Depth: 17 feet
- Fan Size: 10 horsepower
- Pack Factor: 1.5$^2$

The initial run computed the base performance values to be:

- Static Head: 3.1 inches of water
- Airflow: 1.1 cfm/bu$^3$
- Temperature Rise Across the Fan: 2.5°F

$^1$This bin would have a capacity of approximately 10,000 bushels.

$^2$Pack factor = the multiplication factor applied to the airflow resistances equation published by Shedd (1953).

$^3$There are several commonly-used methods to express airflow. To avoid confusion, it is defined as the fan delivery rate in cubic feet per minute divided by the accumulated bushels of grain in the bin.
Figure 7 illustrates the effects of varying fan size. Doubling the fan size (horsepower) increased the airflow rate about 25%. Assuming a fan in the typical range of 10-20 horsepower for a 10,000 bushel bin, the temperature rise (°F) across the fan is about 1 unit less than the static head (inches of water).

Figure 8 illustrates that varying grain depth has a major effect on airflow rate. Doubling the grain depth reduces the airflow about 60%. Static head increased about 60% for each doubling of grain depth. Temperature rise across the fan increased almost linearly from 1.8 to 2.5°F as grain depth increased from 4 to 16 feet.

Figure 9 displays the effect of varying airflow resistance, due to the pack factor. The effective pack factor can be below 1.0 for bins equipped with stirring devices and may exceed 1.5 for an unstirred bin filled using a centrifugal grain spreader. The static head increased about 50 percent as the pack factor increased from 0.8 to 1.6. The temperature rise across the fan increased approximately 20 percent as the pack factor doubled while the airflow decreased about 20%. In summary, Figures 7, 8 and 9 illustrate that fan size and grain depth are critical design variables that affect airflow rate.
Figure 7. The effect of varying fan size on the "base" bin using the FALDRY fan model.
Figure 8. The effect of varying grain depth on the "base" bin using the FALDRY fan model.
Figure 9. The effect of varying pack factor on the "base" bin using the FALDRY fan model.
CONCLUSIONS

FALDRY is a user-oriented low-temperature corn drying model. It can accurately simulate drying for a system of 1 to 6 grain bins with axial fans. FALDRY has the flexibility to accommodate layer filling and is able to adequately predict grain moisture profiles for such a system with high airflow rates.

The precision of the input variables is the most limiting factor in the simulation accuracy of FALDRY. Next in significance are the assumptions of uniform air distribution and grain properties such as density and equilibrium moisture. FALDRY is a potentially-valuable tool that can be used to optimize the design of low-temperature drying systems.

Based on the analysis used to develop the FALDRY fan model the following design criteria are recommended for low-temperature drying bins:

- Maximum grain depth of 16-20 feet.
- Maximum static head of 3-4 inches of water.
- Minimum airflow rate of 1 cubic feet per minute per bushel for a full bin.
- Use of high-efficiency axial fans (Large bins may require 2 or more fans).
- Layer-filling for efficient drying and control of the grain deterioration risk.
The following tasks are suggested for future study and development:

1. Determine the range of variability for the equilibrium moisture content of corn as a function of pedigree, soil type, and climate.

2. Gather field data on the cfm per watt performance curves for axial and centrifugal fans.
REFERENCES


APPENDIX A: FALDRY USER'S GUIDE

General

The FALDRY program is a subroutine package that can simply be added to any existing FORTRAN program. The low-temperature drying model is accessed with a standard subroutine call to subroutine FALDRY, i.e., CALL FALDRY. All the input simulation variables (fan/bin characteristics, weather data, incoming grain, and output options) are transferred to the FALDRY subroutines through a common statement in the main program. Figure A.1 displays the necessary common statement.

```
COMMON/GRNDRY,GRNHAR(6,100,3),FALWTH(150,3),STORGR(6,20,7),
* IPRT,SUPHET(6,2),PACFAC,DATE(150,3),IFINSH,OVRFL,FMTA,FMTM,
* BIN(6,3),EXCRN,CUMB,SFMSB,HEAdd,DEPTh,CUMSW,FANHRS,
* NB,NY,IDAY,IFANON,LAYER,BPSI,MAXLAY,DEPLAY,RH,LPRINT
```

Figure A.1. Required FALDRY common block

FALDRY outputs printed information to I/O units 1, 3, 4, and 6. Appropriate JCL must be supplied by the user to assign the above I/O units to a line printer. I/O unit 1 and 3 output headings with a line summary of fall and final shutdown conditions, respectively.

Unit 4 prints a summary of the filling schedule if subroutine OPTDRY is called. Subroutine print outputs a full page status report of drying system to I/O unit 6. The full page status report as illustrated in Figure A.2 is particularly helpful for debugging and teaching purposes.
Figure A.2. FALDRY output format
The frequency of full page status reports is controlled by the user by initiating variable LPRINT.

FALDRY was designed to run on the IBM compatible FORTRAN H compiler at Iowa State University. It required approximately 100K of core. Simulation of 1 bin over 18 drying seasons executed in about 50 seconds at a cost of roughly 10 dollars.

**Input Variables**

All the following variables must be initialized in the main program before a successful call to FALDRY can be executed.

**NB** - Integer Variable

Bin identification number - 1 to 6

**NY** - Integer Variable

Equal year of simulated season minus 1950

(If NY = 25 [Simulation year 1975] simulation terminates on 16 December)

**MAXLAY** - Integer Variable

Simulated number of layers in the bin - 1 to 20

**LPRINT** - Integer Variable

Controls the frequency of calls to subroutine PRINT

= 3 calls PRINT daily

= 2 calls PRINT weekly

= 1 call PRINT bimonthly

= 0 calls PRINT only on shutdown days

= -1 no calls to PRINT
PACFAC - Real Variable

The pack factor used for Shedd's curve. Typically use

- = 1.5 for layer bin
- = 1.2 for stirred bin

IDATE(I,K) - Integer Array

Contain the calendar date in three increments of A4 format; K = 1, 2, 3 are the respective increments of a complete date listing.

I = 1 to 100 corresponds to Julian dates 251 (September 7) to 350 (December 16) respectively

I = 101 to 150 corresponds to Julian dates 91 (April 1) to 140 (May 20) respectively [Leap years are ignored]

SUPHET(L,K) - Real Array

Amount of supplement heat

L = Bin Number

K = 1 supplement electric heat in BTUs per minute

(supplement heat energy added to cumulative KWHs used)

K = 2 supplement heat in °F (only electric fan energy included in cumulative KWHs used)

BIN(I,K) - Real Array

Fan bin specification in English units

I = Bin identification number 1 to 6

K = 1 bin diameter (ft)

K = 2 bin depth (ft)

K = 3 fan size (Hp)
FALWTH(I,K) - Real Array

24 hour averages of daily weather data

K = 1 ambient temperature (°F)
K = 2 relative humidity
K = 3 absolute humidity ratio

I = 1 to 100 corresponds to Julian dates 251 (September 7) to 350 (December 16) respectively
I = 101 to 150 corresponds to Julian dates 91 (April 1) to 140 (May 20) respectively [Leap Years are ignored]

GRNHAR(L,I,K) - Real Array

Incoming wet grain flow data

K = 1 quantity (bushels)
K = 2 moisture (% MCWB)
K = 3 temperature (°F)

I = 1 to 100 corresponds to Julian dates 251 (September 7) to 350 (December 16) respectively

L = bin identification number 1 to 6

NOTE:

Fall or final fan shutdown cannot occur until the user indicates he has finished filling the bin by setting the incoming bushels equal to '-1.0' for each bin for the day following the last grain input.
Key Internal Variables

CUMBU - Real Variable
Total number of bushels in the bin.

CFMSF - Real Variable
The cubic feet per minute of airflow per square foot of bin floor.

HEAADD - Real Variable
The air temperature rise ($^\circ F$) across the fan and heater.

CUMKWK - Real Variable
The total to date electrical usage of motor and heater. (K.W.H.)

IPRT - Integer Variable
A daily status variable that controls whether or not subroutine PRINT will be called.

IFINSH - Integer Variable
A seasonal status variable that indicates if the bin filling has been completed. IFINSH must equal '1' before the drying fan can shutdown.

OVRFIL - Real Variable
The number of bushels that constitute overfilling of the bin.
They are ignored by the drying model.

EXCGRN - Real Variable
The number of bushels that are assigned to the top layer in the bin.

FANHRS - Real Variable
The total to date number of operating fan hours.
IDAY - Integer Variable

IDAY is the model's indicator of the calendar date.

IDAY = 1 to 100 & 101 to 150 corresponds to Julian Dates 251 (September 7) to 350 (December 16) & 91 (April 1) to 140 (May 20) respectively.

IFANON - Integer Variable

A daily status variable that indicates if the fan is off or on.

LAYER - Integer Variable

The number of the top layer in the bin that contains grain; can vary between 1 and the value for MAXLAY since the bin need not be full.

BULAY - Real Variable

The maximum capacity of a simulated layer (bushels).

DEPTH - Real Variable

The actual grain depth in the bin (feet).

BPSI - Real Variable

The static pressure in the plenum (in./H₂O).

DEPLOY - Real Variable

The depth of each simulated layer (ft.).

RH - Real Variable

The relative humidity of the air in the plenum.

STORGR(L,I,K) - Real Array

This array contains all the pertinent data on the stored grain. It is recommended that all the values of STORGR be initialized to zero before a call to FALDRY is executed.

K = 1 Grain Temperature (°F)
K = 2 Wet base moisture (%)
K = 3 Dry base moisture (%)
K = 4 Change in moisture since last call to subroutine PRINT
   (% MCWB)
K = 5 Cumulative grain deterioration (% dry matter loss)
K = 6 Cumulative equivalent storage time as calculated by subroutine SAFES
K = 7 The original dry base moisture content of grain
I = Layer identification number 1 to 20
L = Bin identification number 1 to 6

FMTA - Real Variable
Average moisture content (% wet base) for final shutdown.

FMTM - Real Variable
Maximum moisture content allowed in any layer for final shutdown.

ADDITIONAL USER SUBROUTINES

1. CALL BEGNRN

This statement must be the first card in the executive program. It
sets up the FALDRY subroutine package and prints summary headings:

Initial Parameter Values

All Bins - 30' Diameter
17.5' Grain Depth
10 Hp. Fan
No Supplemental Heat

10 Layer Simulation
1.5 Shedd's Pack Factor

Short Print Option (LPRINT = 0)

Any of these parameters can be reassigned after the call to BEGNRN.

2. CALL BEGNMR

This statement must be executed before each sequence of calls (NB = 1 - 6) to FALDRY or OPTDRY. It initializes all values in arrays STORGR and GRNHR to zero.

3. CALL AUGWTH

This statement reads in an average central Iowa weather year base on weekly averages over a 28-year period.

4. CALL OPTDRY

This call is used in place of CALL FALDRY. It both layer-fills and simulates drying in the bins. It assumes a 20-layer simulation and requires that GRNHR array contains the field moisture profile of the corn versus date. The bin is layer-filled using the "optimum filling strategy" that continuously monitors the conditions in the bin and the grain moisture in the field. A summary of the filling schedule will be printed by I/O unit number 4.

5. CALL MSTPRF (I)

This statement fills GRNHR with an average filled moisture profile. (can be used with the OPTDRY CALL)

I = 1 Early Season
I = 2 Average Season
I = 3 Late Season

PSYSUN is a computer model of a psychrometric chart

DB - Dry Bulb Temperature (°F)

WB - Wet Bulb Temperature (°F)

R - Moisture Ratio (lb H₂O/lb Dry Air)

H - Enthalpy (BTU/lb Dry Air)

DP - Dew Point Temperature (°F)

SV - Specific Volume (ft³/lb Dry Air)

M - Function Selector

<table>
<thead>
<tr>
<th>M</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DB, WB</td>
<td>R, W, H, DP, SV</td>
</tr>
<tr>
<td>2</td>
<td>DB, R</td>
<td>WB, W, H, DP, SV</td>
</tr>
<tr>
<td>3</td>
<td>DB, W</td>
<td>WB, R, H, DP, SV</td>
</tr>
<tr>
<td>4</td>
<td>DB, H</td>
<td>WB, R, W, DP, SV</td>
</tr>
<tr>
<td>5</td>
<td>DB, DP</td>
<td>WB, R, W, H, SV</td>
</tr>
</tbody>
</table>
APPENDIX B:
FORTRAN LISTING
OF FALDRY
SUBROUTINE BEGIN
COMMON/GNDRY/GNMAH/6,100,3),FALWTH/150,3),STORGR/1,20,7),
*IPMT,SUPHET(6,2),PACFAC,DATE/150,3),IFINGUNVFIL/FMTA,FMTM,
*BIN(6,3),EXCXGN,CUMD,CFMF,HEAAdd,STORLAY,DEPEQ,CUNKNH,FAMN
*NY,NDAY,IFANGN,LAY=,BPSI,MAXLAY,DEFLAY,RM,PRINT
DO 23 IK=1,6
SUPHET(IK)=0.0
23 DO 25 K=1,6
RIN(K,1)=10.0
RIN(K,2)=17.0
RIN(K,3)=10.0
25 CONTINUE
PACFAC=1.5
FMTA=14.5
FMTM=15.5
MAXLAE=10
LPRINT=0
WRITE(1,4001)
14001 FORMAT(*'SUMMARY OF SIMULATED DRYER RESULTS'/*,6)
*35X,'FINAL SHUT DOWN CONDITIONS'/*,20.
**MODEL BUSHELS BIN FAN FAN KT**S **GRAIN MLIST*G**22.
**DETERIORATION** GRAIN CFM/BU TEMP, BIN BIN BUSHELS**/*,5.
**YEAR FILL NG**, OFF HOURS USED AVG. MAX. LAY*/*,24.
**AVG. MAX. LAYER TEMP. FINAL RISE DIA. M**TH HP. IGNUEL/*)25.
WRITE(3,4003)
14003 FORMAT(*'SUMMARY OF SIMULATED DRYER RESULTS'/*,67.
*35X,'FINAL SHUT DOWN CONDITIONS'/*,20.
**MODEL BUSHELS BIN FAN FAN KT**S **GRAIN MLIST*G**22.
**DETERIORATION** GRAIN CFM/BU TEMP, BIN BIN BUSHELS**/*,5.
**YEAR FILL NG**, OFF HOURS USED AVG. MAX. LAY*/*,24.
**AVG. MAX. LAYER TEMP. FINAL RISE DIA. M**TH HP. IGNUEL/*)25.
RETURN
END
SUBROUTINE PSYN
COMMON/GNDRY/GNMAH/6,100,3),FALWTH/150,3),STORGR/1,20,7),
*IPMT,SUPHET(6,2),PACFAC,DATE/150,3),IFINGUNVFIL/FMTA,FMTM,
*BIN(6,3),EXCXGN,CUMD,CFMF,HEAAdd,STORLAY,DEPEQ,CUNKNH,FAMN
*NY,NDAY,IFANGN,LAY=,BPSI,MAXLAY,DEFLAY,RM,PRINT
C ZERO STORGR ARRAY
DO 981 J3=1,20
DO 981 K3=1,7
STORGR(I3,J3,K3)=0.0
981 CONTINUE
C ZERO GNMAH ARRAY
DO 982 I=1,100
DO 982 K=1,3
982 CONTINUE
C RETURN
END
SUBROUTINE AUTHOR-- TSENG-YUA SUN 1971
C HEATING,PIPING & AIR CONDITIONING* 43(II/14B-100
C PSYCHOMETRIC SUBROUTINE USING A+SIGMA+ALPHA+ALGORITHMS
C------------ FJX=1, INPUT=1, Output=5.5, M,D,P,S
C------------ FJX=2, INPUT=1, Output=5.5, M,D,P,S
C------------ FJX=3, INPUT=1, Output=5.5, M,D,P,S
C------ FOR N=4, INPUT=DB, M=4, OUTPUT=DB, M=4, SV
C------ FOR N=5, INPUT=DB, M=5, OUTPUT=DB, M=5, SV
DATA PU,FS/29.22,1.00,45/0.64/2.0,0.0/4.0/1.0
GO TO(10,20,10,50,15)
10 PVP=PV(DB,WB,HU,FS)
   =G0.622*FS*PVP/(PD-FS*PVP)
   =PV/PVSF(DB)
   GO TO 15
20 W=WF(DB,P8,FS)
   GO TO 25
50 PVP=PVSF(DB)
   =G0.622*FS*PVP/(PD-FS*PVP)
   GO TO JO
40 "W=0.622*FS*PVP/(PD-FS*PVP)"
30 R=RSPF(W,W,PD,FS)
25 WB=WBF(DB,W,FS)
15 DP=OPF(DB,W,FS)
45 H=0.622*DP/(DP-H0.*W)
55 RETURN
C SPECIFIC VOLUME AT TEMPERATURE DB AND HUMIDITY HU
SV=(53.352*(459.67*HU)/(PD+70.7*0.2)^*(1.0*0.75*W))"
RETURN
END
C SATURATED VAPOR PRESSURE AT TEMPERATURE DB
FUNCTION PVSF(DB)
DATA A*/8#/C/-7.9029d.5.02098,-1.38163-7/87.
DATA D#d,F/111.344.8,1341.8-3,3.49139/88.
DATA G,HeP#0/-9.09713,-3.36654,6.02739*3/89.
T=(D8*459.67#F/1.890.
IF(TL.T.273.16)GO TO 391.
Z=373.16/T 92.
S=A*(Z-1.0)*H ALOG10(Z)*C*(1.0*(1.0+1.0/Z)-1.0)
S=S*E*(10.0*(F*(Z-1.1)-1.1)
GO TO 4 94.
3 Z=273.16/T 95.
S=S*E*(Z-1.1)*H ALOG10(Z)*P*(1.0+1.0/Z)+ALUG10(O)
GO TO 4
4 PVSF=29.921*1.0*55.
RETURN
END
C VAPOR PRESSURE AT TEMPERATURES DB AND WB
FUNCTION PV(DB,WB,PD,FS)
R=0.0
PV=PVSP(WB)
IF(DB.L.E.WB GO TO 4
WS=0.622*PVSP/(PD-PV)
IF(WB<GT.32.0)GO TO 2
PV=PVSP-5.704E-4*PD*(DB-WB)/1.0
GO TO 3
6 PV=PVSP
GO TO 3
2 CDB=(DB-32.0)/1.8
CWB=(WB-32.0)/1.8
HL=57.310.4409*(CDB-CWB)
CH=0.2402*0.4409
EX=(WS-CH*CDW-CWB)/HL/3.02
PV=PV*EX/1
PV=PV+EX/(1.0*EX)
IF(K.GT.0.01)GO TO 3
131

R=P/V/P/SF(0 DB)
IF(R GT 0.1) GO TO 3
WS=0.622*FS*PVS/(P8-FS*PVS)
GO TO 2
RETURN
3 RETURN
END

C HUMIDITY RATIO AT TEMPERATURE DB AND RELATIVE HUMIDITY R
FUNCTION WPS(DB, PB, FS)
WS=0.622*FS*PVS/(P8-FS*PVS)
R=WS/0.622
DS=WS/(P8-FS*PVS)/(P8-FS*PVS)
WPS=WS*DS
RETURN

C RELATIVE HUMIDITY AT TEMPERATURE DB AND HUMIDITY RATIO W
FUNCTION RF(DB, W, PB, FS)
PVS=PVDF(DB)
W=0.622*FS*PVS/(P8-FS*PVS)
DS=W/WS
R=DS/(1.0-(1.0-DS)*FS*PVS/P8)
RETURN

C OP TEMPERATURE AT TEMPERATURE DB AND HUMIDITY R
FUNCTION DP(F(DB, W, PB, FS)
W=DB
PVD=P/F*(1.0+622)*(W/FS)
1 IF(PV>10.0)10
W=10.0
10 RETURN

SUBROUTINE MSTPRF(1)
COMMON/GRNDRY/GRNHAR(6,100,3),FAL*TH(150,3),STORGR(6,20,7)
* IPRT,SUPHET(6,2),PACFAC,DATE(150,3),IFINSH,OVRFIL,FMTH,
* 0N6,PUBIL,CUMKH,CUMU,PWSF+MACADD,BULAY,DEPTH,CUMKH,FANHS,
* 0N6,PUBIL,DATE,UP PHYS,MAXLAY,DISPLAY,RMTPRINT
SIMWST=28
DG=33 ISDAY=3
IF(1.0>0)1 GO TO 32
IF(1.0>3)3
IF(ISDAY.EQ. 30) SIMMST=24.
IF(ISDAY.EQ. 37) SIMMST=22.
IF(ISDAY.EQ. 44) SIMMST=20.
IF(ISDAY.EQ. 51) SIMMST=18.
GO TO 934.
22 IF(ISDAY.EQ. 30) SIMMST=26.
IF(ISDAY.EQ. 37) SIMMST=24.
IF(ISDAY.EQ. 44) SIMMST=22.
IF(ISDAY.EQ. 51) SIMMST=20.
GO TO 934.
33 IF(ISDAY.EQ. 30) SIMMST=28.
IF(ISDAY.EQ. 37) SIMMST=26.
IF(ISDAY.EQ. 44) SIMMST=24.
IF(ISDAY.EQ. 51) SIMMST=22.
GO TO 934.
934 DO 5632 L4=1,6
GRNHAR(L4,ISDAY,1)=1.
GRNHAR(L4,ISDAY,2)=SIMMST.
GRNHAR(L4,ISDAY,3)=AVG.
5632 CONTINUE.
RETURN.
END.
SUBROUTINE AVG.
COMMON/GRNDRY/GRNHAR(6,100),FALWTH(150),STORGR(6,3),711,
*IPRT,SUPNET(20),PACLFA,DATE(150,3),IFMONTH,WBRFL,FHTA,FHTM, 234.
*EXCMNF,CUMNB,CFNSMF,HEADA0,HULAY,DEPHTM,CUMKMH,FANHRIS, 20X.
*NB,Y:DAY;FADD,CYCLE,PSI;MAY,LY,DATEY,RLPRINT.
INTEGER IMON/(150,3),D,MONTH(6),AVG.
REAL MR(20),DB(20),RHT(20),WRH(20).
IMON=1.
DO 10 1IDAY=1,150
IF(IMON.EQ.1.AND.IMON.DY.GT.30) GO TO 20.
IF(IMON.EQ.2.AND.IMON.DY.GT.31) GO TO 20.
IF(IMON.EQ.3.AND.IMON.DY.GT.30) GO TO 20.
IF(IMON.EQ.4.AND.IMON.DY.GT.30) GO TO 20.
IF(IMON.EQ.5.AND.IMON.DY.GT.30) GO TO 20.
25 IDATE(1,DAY,1)=MONTH(IMON)
IDATE(IDAY,2)=IMONY(1)
IDATE(IDAY,3)=AVG.
IMONY=IMONY+1.
IMON=IMON+1.
GO TO 20.
10 CONTINUE.
DO 60 I=1,20
CALL PSYSUN(DB(1),MR(1),RHT(1),WRH,PSV,X1)
1WK=1.
DO 70 ISDAY=1,150
IF(ISDAY.EQ.17) 1WK=3.
132
IF(ISDAY.EQ.24) WK=4
IF(ISDAY.EQ.31) WK=5
IF(ISDAY.EQ.39) WK=6
IF(ISDAY.EQ.47) WK=7
IF(ISDAY.EQ.55) WK=8
IF(ISDAY.EQ.63) WK=9
IF(ISDAY.EQ.71) WK=10
IF(ISDAY.EQ.79) WK=11
IF(ISDAY.EQ.87) WK=12
IF(ISDAY.EQ.95) WK=13
IF(ISDAY.EQ.103) WK=14
IF(ISDAY.EQ.111) WK=15
IF(ISDAY.EQ.119) WK=16
IF(ISDAY.EQ.127) WK=17
IF(ISDAY.EQ.135) WK=18
IF(ISDAY.EQ.143) WK=19
IF(ISDAY.EQ.151) WK=20
IF(ISDAY.EQ.159) WK=21
FALWTH(ISDAY,1)=DB(1,WK)
FALWTH(ISDAY,2)=RHT(1,WK)
FALWTH(ISDAY,3)=SL(1,WK)
70 CONTINUE
NY=-100000
RETURN
END
SUBROUTINE OPTORY
COMMON/GRNHAR(6,100,3),FALWTH(150,3),STORGRC
* XPRT,SUPHET(6*2)*PACFAC*10ATEC150*31*IFINSH*OVRFIL*FMTA*FMTH*
$B1N(6*3)*EXCGRN*CUMBU*CFM5F*HEAADD*BULAY*DEPTH*CUMKWH*FANHRS*
*NBY,N1DAY,IFANON,LAYER,HP51,MAXLAY,DEPLAY,RLM,PRINT
REAL NGD
HAXLAY=20
DEPTH=0.0
CFMSF=0.0
FANHRS=0.0
CUMKWH=0.0
IDAY=1
IFANON=0
LAYER=1
EXCGRN=0.
CUMBU =0.
IFINSH=0.
OVRFIL=0.0
WRITE(4,1326)
1326 FORMAT(*,1326 FORMAT.CO, ' DATE/BN FL CFM/CFM/BU TOTAL WET ADDestb.3)
#D BUSHELS MCWB GRAIN*/' ',204,
* /PLACE NO DT DT F/2 (WET) DEPTH DEPTH DE 205,
#OTH ADDED TTP*/
206.
IFILDY=0
STRMST=26.
10 IF(200*NB*IDAY+2).GT.0.0.AND.GRNHAR(NB,1DAY,2).LE.STRMST) 208.
# GO TO 15
IF(IDAY.EQ.100) RETURN
15 IDAY=IDAY+1.
GO TO 10
13 IDAY=IDAY+1
204.
15 IF(IFINSH.EQ.10) GO TO 21
205.
IF(IDAY.EQ.100)IFINSH=1
206.
1GODAY=1
207.
ODDRY=0.0
208.
IF(STORGRC(NB,1,2).EQ.0) GO TO 110
209.
DO 100 I=1,LAYER
  IF(STORGR(NB,1,2).LE.175000D0)FGET=(FLOAT(I)/FLOAT(4+LAY))
  #BIN(NB,2))
100 CONTINUE
  WGO=DEPTH-DOORY
  IF(LDYS=1,1D0)
  IF(CMSF=EG.0.0.25FMSF=2.5*1300.*BIN(NB,3)/(BIN(NB,1)**2*1.1494/4)507.
  CMSF=CMSF
  C
  IF(GRNHR+NB,JDAY.2).LE.0.0 GO TO 230
  IGDAY=1
  ADD=1.0
  GO TO 232
230 CONTINUE
  GMST=GRNHAR(NB,JDAY.2)
  IF(GMST+LT.24.0) AIM=(GMST-17.4/0
  IF(GMST.24.0) AIM=GMST-20
  C
  IF(AIR+LT.50)AIR=50
  TGO=CMSF/(AIR**1.249
  ADD=TDG-WGO
  IF(ADGO.2).LT.0.01 ADGO=-0.001
  IF(GMST+LT.26.0) ADGO=2.0
  IF(ADGO.24.0) ADGO=0.0
  LAYCR=IF(I(FLOAT(LAYR)**2.11))
  IF(LAYR.2).LT.2) LAYR=2
  IF(GMST+LT.22.0) STORGR(NB,LAYR.1).LT.17.5) AIM=0.0
  IF(ADGO.2).LT.1 GO TO 232
1F(LFREE=I
  ADGD=BIN9NB,2)-DEPTH
  232 CONTINUE
  NGO=OEPTH*AIM
  GHRAR+NB,JDAY.1)=ADGO*(BIN(NB,1)**2*1.1494/4.1.249)+0.1
  WRITE(1,1001) (DATE(I,JDY,J,3),JN=1,3),NB,IFILDY,IGDAY,CMSF,AIM,
  #NO, WGO,ADGO,GRNHAR(NB,JDAY,K),K=1,3)
1001 FGHMATE.1,366,J3,9.17P1)
  IF(GRNHR+NB,JDAY.1).LT.10.0 GO TO 2119
  CALL FILL
  C
  IF(EXCGRN.1).LT.1 CALL EXGRN
  CALL FAN
2119 IF(STORGR+NB,1,2).LT.0.0 GO TO 13
  #= 0
  IF(STORGR+NB,1,2).EQ.0.0 RETURN
  C
  C
  IF(FAO=0.0) GO TO 18
  IF(ILINT+LT.1) GO TO 17
  IF(FIDAY=0.0) 1PR=1
  IF(FIDAY=E.01) 1PR=1
  IF(FIDAY=0.41) 1PR=1
  IF(FIDAY=0.8) 1PR=1
  IF(FIDAY=0.0) 1PR=1
  IF(FIDAY.E.0.1) 1PR=1
  IF(FIDAY=0.1151) 1PR=1
  IF(FIDAY=0.129) 1PR=1
  134
IF(IDAY.EQ.143) IPRT=1
IF(IPRT .LT. 2) GO TO 17
IF(IDAY.EQ.20) IPRT=1
IF(IDAY.EQ.34) IPRT=1
IF(IDAY.EQ.48) IPRT=1
IF(IDAY.EQ.62) IPRT=1
IF(IDAY.EQ.76) IPRT=1
IF(IDAY.EQ.90) IPRT=1
IF(IDAY.EQ.104) IPRT=1
IF(IDAY.EQ.118) IPRT=1
IF(IDAY.EQ.132) IPRT=1
IF(IDAY.EQ.146) IPRT=1
IF(IPRT .LT. 3) GO TO 17
IPRT=1
17 CONTINUE
IF(IPRT.EQ.0) CALL PRINT
16 IF(IDAY.EQ.150) RETURN
IDAY=IDAY+1
IF(IFANON.EQ.0) GO TO 24
CALL VANCE
24 IF(IFANON.EQ.0.AND.IFINSH.EQ.1) RETURN
25 IF(IDAY .LT. 150) GO TO 15
RETURN
END
SUBROUTINE FALODY
COMMON/GRNDRY/GRNHAR(6,100:3),FALWTH(ISO,3),STORGR(6,20:7),
* IPRT,SUPHET(6,2),PACFAC,IDATE(150,3),IFINSH,OVRFIL,FMTA,FMTN,
* BINT(6,3),EXCCRG,CUMBU,CFMSP,HEADD,BULAY,DEPTH,CUM##,FANHR$,FANHRS
* NB,NY,IDAY,IFANON,LAYER,10P1,1AXLAY,DEPLAY,RHLPRT
FANHRS=0.0
CUNKWH=0.0
IDAY=1
IFANON=0
CUMBU =0.
IFINSH=0
OVRFIL=0.0
10 IF(1GRNHAR(NB,10AY+1).GT.1.) GO TO 15
IF(IDAY.EQ.100) RETURN
IDAY=IDAY+1
GO TO 10
15 IF(1FINSH.EQ.1) GO TO 21
IF(1GRNHAR(NB,10AY+1).LT.1.) GO TO 20
ENTRY SCORDY
CALL FILL
CALL FAN
GO TO 21
20 IF(1GRNHAR(NB,10AY+1).EQ.-1) IFINSH = 1
21 IPRT = 0
IF(IFANON.EQ.0) GO TO 10
IF(IPRT .LT. 1) GO TO 17
IF(IDAY.EQ.27) IPRT=1
IF(IDAY.EQ.41) IPRT=1
IF(IDAY.EQ.55) IPRT=1
IF(IDAY.EQ.69) IPRT=1
IF(IDAY.EQ.83) IPRT=1
IF(IDAY.EQ.101) IPRT=1
IF(IDAY.EQ.115) IPRT=1
IF(IDAY.EQ.129) IPRT=1
IF(IDAY.EQ.143) IPRT=1
IF(LPRINT .LT. 2) GO TO 17
IF(IDAY.EQ.20) IPRT=1
IF(IDAY.EQ.40) IPRT=1
IF(IDAY.EQ.60) IPRT=1
IF(IDAY.EQ.90) IPRT=1
IF(IDAY.EQ.120) IPRT=1
IF(IDAY.EQ.130) IPRT=1
IF(LPRINT .LT. 3) GO TO 17
IPRT=1
CONTINUE
IF(IPRT.EQ.1) CALL PRINT
IF(IDAY.EQ.150) RETURN
IDAY=IDAY+1
IF(IFANON.EQ.0) GO TO 15
CALL VANCE
24 IF(IFANON.EQ.0.AND.IFINSHEQ.1) RETURN
25 IF(IDAYLT.150) GO TO 13
RETURN
END
SUBROUTINE FILL
COMMON/GRNARY/GENHAR(6,100,3),FALTTH(150,3),STORGR(6,20,7)
* IPRT,SUPMETH(2),PACFAC,LDATE(150,3),IFINSH+VNPFL,FMAFA,FMTA+FBRT,
* BINE(6),EXCGRN,CMUH,CFSF,HLAAUJ,HULAY,DLPTM,CMUNH,FANNHS,
* NB,NY,IDAY,IFANON,LAY£R,BPSI,MAYLAY,RH,LPRINT
DELPAY=BIN(NB,2)/FLOAT(MAXLAY)
BULAY=((BIN(NB,1)+23,1650)/(4*1.245))
HUEPLAY
IF(LAY£L=MAXLAY) GO TO 10
IF(EXCGRNLT.ULAY) GO TO 10
EXCGRN=EXCGRN-GENHAR(NB,IDAY,1)
7 OVFIL=EXCGRN-BULAY
IF(LPRINT.GT.0)WRITE(6,100) (IDAT,IDAY,11=1,3), CwvFil
100 FORMAT(* ' ',************'/',2,A4/!,
* ' THE PIN IS FULL. THE OVERFLOW OF',
* 'BUSHELS WILL BE IGNORED'/' ',************')
RETURN
10 IFANON=1
GRNNEW=GENHAR(NB,IDAY,1)
GRNADD=EXCGRN + GRNNEW
IF(GRNADD.GT.MAXLAY) GO TO 15
R1=EXCGRN
GRNA0J
R2 = GRNEW /GRNA0J
STORGR(NB,LAYER,1) = R1*STORGR(NB,LAYER,2)+R2*GENHAR(NB,IDAY,1)
STORGR(NB,LAYER,2) = R1*STORGR(NB,LAYER,2)+R2*GENHAR(NB,IDAY,2)
STORGR(NB,LAYER,7) = STORGR(NB,LAYER,2)/(100.-STORGR(NB,LAYER,2))
* +100.
R4 = STORGR(NB,LAYER,3)+STORGR(NB,LAYER,7)
EXCGRN=GRNADD
RETURN
15 R1= EXCGRN/BULAY
R2 = 1.-R1
STORGR(NB,LAYER,1) = (R1*STORGR(NB,LAYER,1)+R2*GENHAR(NB,IDAY,1)
STORGR(NB,LAYER,2) = R1*STORGR(NB,LAYER,2)+R2*GENHAR(NB,IDAY,2)
STORGR(NB,LAYER,7) = STORGR(NB,LAYER,2)/(100.-STORGR(NB,LAYER,2))
* +100.
R4 = STORGR(NB,LAYER,3)+STORGR(NB,LAYER,7)
LAYER=LAYER+1
EXCGRN=GRNADD
IF (LAYER GT MAXLAY) GO TO 135
EXCRN = GRNAD - BULAY
10 STORGN(NB.LAYER.1) = GRNAD(NB.DAY.1)
STORGN(NB.LAYER.2) = GRNAD(NB.DAY.2)
STORGN(NB.LAYER.7) = (STORGN(NB.LAYER.2) - (100 - STORGN(NB.LAYER.1))
* 100.
STORGN(NB.LAYER.3) = STORGN(NB.LAYER.7)
IF (EXCRN LT BULAY) GO TO 16
LAYER = LAYER + 1
IF (LAYER GT MAXLAY) GO TO 135
EXCRN = EXCRN - BULAY
GO TO 16
135 LAYER = MAXLAY
GO TO 7
20 RETURN
END

SUBROUTINE FAN
COMMON/GRNAD,GRNHAH(6.100.3),EXCRN(6.2),STORGN(6.2),1.
* IPRT, SUPHET(6.2), PACFAC, DATE(150.3), IFINSH, GVRFL, FMTA, FMTM,
* BIN(6.3) EXCRN, CUMDB, CFMSF, HEAADD, BULAY, DEPTH, CUMKWH, FANRS,
* NB.NY.IDAY.IFANON.LAYER.BPS1.MAXLAY.DEPLAY.RH.LPRINT
EXTERNAL MERIT1
AREA = (BIN(NB.1)**2*3.14159)/(4.)
DEPTH = IFLOAT(LAYERI-1.*EXCRN/DEPLAY)
IF (DEPTH GT BIN(NB.2)) DEPTH = BIN(NB.2)
CUMDB = BULAY*DEPTH/DEPLAY
IF (DEPTH GT BIN(NB.2)) DEPTH = BIN(NB.2)
CALL VARSEC(MERIT1.16.+CFMSF)
CFMSF = CFMSF
AIRLBS = AREA*CFMSF/12.75
HEATMT = ((BIN(NB.3))/.5)**42.44 + SUPHET(NB.1)
HEAADD = HEATMT/(AIRLBS*.243)
HEAADD = HEAADD + SUPHET(NB.2)
IF (IPRT EQ 1) IPRT = 1
RETURN
END

SUBROUTINE MERIT1(CFMSF, ERROR)
COMMON/GRNAD,GRNHAH(6.100.3),EXCRN(6.2),STORGN(6.2),1.
* IPRT, SUPHET(6.2), PACFAC, DATE(150.3), IFINSH, GVRFL, FMTA, FMTM,
* BIN(6.3) EXCRN, CUMDB, CFMSF, HEAADD, BULAY, DEPTH, CUMKWH, FANRS,
* NB.NY.IDAY.IFANON.LAYER.BPS1.MAXLAY.DEPLAY.RH.LPRINT
AREA = (BIN(NB.1)**2*3.14159)/(4.)
FPSI = 7.5*11. - ((CFMSF1*AREA1/1000.)/(1.8*BIN(NB.3)))
BPSI = DEPTH* (.00065*CFMSF1**2/ALUG(1.156*CFMSF1)) * PACFAC
ERROR = FPSI - BPSI
RETURN
END

SUBROUTINE VARSEC(F,G,MON,2)
LCOUNT=0
X=0
XX=XX+0.001
IF (X.EQ.0.) XX=0.001
CALL FXX, BI
IF (MON EQ 0) WRITE (6,12)
12 FORMAT(1X, CONVERGENCE MONITOR SUBROUTINE VARSEC*)
2 GO TO 16
16 NEW X)
CALL FXX A)
C **** CALCULATE SLOPE

C

10 LL=0
D=(A-B)/(X-XX)
15 IF(LL.GT.0.00690 GO TO 50
E=A/D
C **** OBTAIN A NEW ESTIMATE OF THE ROOT
C

C Z=E
LCOUNT=LCOUNT+1
IF(LCOUNT.EQ.1)WRITE(6,20) X,A,D,Z
20 FORMAT(5G16.7)
IF(LLGT.GT.25)GO TO 30
EZ=ABS(E)
IF(ABS(Z).GT.1.0c-6l EZ=ABS(E/Z)
C **** CHECK THE MAGNITUDE OF THE ERROR
C

C IF(EZ.LT.«0.005)GO TO 60
IF(EZ.LT.«0.05.AND.LCOUNT.GT.25)GO TO 60
XX%=EZ
B=A
X=Z
CALL FCXtAI
IF(C.EQ.0.0)GO TO 60
IF(C.EZ.GT..0.02)GO TO 10
IF(LL.GE.3IG0 TO 10
LL=LL+1
GO TO 15
30 WRITE(6,40) Z
40 FORMAT('0$#*** ERROR MESSAGE SUBROUTINE VARSEC $*$**#/ 573.
1* THE FIRST DERIVATIVE OF THE FUNCTION IN THE NEIGHBORHOOD'/ 573.
2* OF BIt*G14.7.' WAS EQUAL TO 0. AN ESTIMATED FOR THE ROOT*/ 573.
3* OF THE FUNCTION COULD NOT BE OBTAINED SO THE SEARCH WAS'/ 573.
4* TERMINATED.*) 573.
50 HRITE(6.70>X
70 FORMAT('0$#*** ERROR MESSAGE SUBROUTINE VARSEC $*$**#/ 573.
1* THE FIRST DERIVATIVE OF THE FUNCTION IN THE NEIGHBORHOOD'/ 573.
2* OF BIt*G14.7.*/ 573.
3* IS Bi*.G14.7./* INVESTIGATION OF THE FUNCTION IS RECOMMENDED.*) 573.
C GO TO 60
G0 TO 60
60 RETURN
END
C SUBROUTINE PRINT
COMMON/GRN0RY/GRNHAR(6,100,3) .FAL#TH( 150,3) • STCIRGR ( 6 *20 • 7 ) , 586.
* IPRT,SUPHET(6*2).PACFAC,IDAT£ClS0t3)t1FINSHtOVRFIL«FMTA«FMTM* 586.
*BIN<6f3)*EXCGRN,CUMBUtCFMSF«HEAA0D«aULAY»0EPTH*CUMKWH,PANHHS» 586.
*Nb,Ny,IDAY,IFANON.LAYERtBPS!•MAXLAY•DEPLAY•RH•LPRINT 586.
REAL AVG(5)
REAL NRV=NUMLAY
DO 36 K=1,LAYER
36 STORGR(NB,K,4)=STURGR(NB,K,4)-STORGR(NB,K,2)
JYR =JYR+50
DO 40 I=1,5
AVG(I) =0.0
DO 30 KK=1,LAYER
AVG(I)=AVG(I)+STORGR(NB,KK,1)/FLOAT(LAYER)
C
CONTINUE

CCNTINUE 600.
CONTINUE 631.
CONTINUE 662.
 CONTINUE 693.

10 1DAYK=1DAY
IF (1DAYK.GT.100) 10AVKK=100
WRITE(6,100) (LDATEC10AY,K1),K1=1,3)
(1AVAT(10AY,K1)),K1=1,2)
1 IFANON,NB,FANHRS,BPS,BINING,B),(CFMSF,UNINU),
HEADD,BINEG2),CUMBD,BUDIN,GRNHARMN,1DAYKK1),HULAYJ,ULPTH,
2MAXLAY,EXCRN,CUMKK

100 FORMAT(*'1/0''*0''10X,*DATE/PLACE...**3A4 ''0'',
*AVTKAGE TEMP. (F) *F6.1'/0''*F6.1/**F*10X,AVERAGE REL. HUM. *F6.1,
2FAN CUTOFF 1 = ON) ''0''''F6.1,'FAN HOURS. 'F6.1/'0'*,
3STATIC HEAD IN HZ1...''F6.1,'HOURS...''F6.1,'TOTAL BUSHELS IN BIN...''F6.1,'HOURS...''F6.1,
4TEMP. RISE DEG. F =0' ''F6.1,'TOTAL BUSHELS IN BIN...''F6.1,'HOURS...''F6.1,
5GRAIN DEPTH (FT)''F8.2,'TOTAL # OF LAYERS...''F6.1,’HOURS...''F6.1,
6BU. IN LAST 24 HOURS...''F8.1,'HOURS...''F6.1,'HOURS...''F6.1,
7GRAIN MOISTURE-PERCENT WET BASE...''F6.1,'GRAIN TEMPERATURE-DEGREES FAHRENHEIT...''F6.1,
8MOISTURE REMOVED-PERCENT WET BASE...''F6.1,'CUMULATIVE GRAIN DEVIATION...''F6.1,
9AVERAGE GRAIN MOISTURE(PERCENT)='F6.1,'AVERAGE DETERIORATION...''F6.1,

102 FORMAT(*'1/0''*0''10X,*DATE/PLACE...**3A4 ''0'',
*AVTKAGE TEMP. (F) *F6.1'/0''*F6.1/**F*10X,AVERAGE REL. HUM. *F6.1,
2FAN CUTOFF 1 = ON) ''0''''F6.1,'FAN HOURS. 'F6.1/'0'*,
3STATIC HEAD IN HZ1...''F6.1,'HOURS...''F6.1,'TOTAL BUSHELS IN BIN...''F6.1,'HOURS...''F6.1,
4TEMP. RISE DEG. F =0' ''F6.1,'TOTAL BUSHELS IN BIN...''F6.1,'HOURS...''F6.1,
5GRAIN DEPTH (FT)''F8.2,'TOTAL # OF LAYERS...''F6.1,’HOURS...''F6.1,
6BU. IN LAST 24 HOURS...''F8.1,'HOURS...''F6.1,'HOURS...''F6.1,
7GRAIN MOISTURE-PERCENT WET BASE...''F6.1,'GRAIN TEMPERATURE-DEGREES FAHRENHEIT...''F6.1,
8MOISTURE REMOVED-PERCENT WET BASE...''F6.1,'CUMULATIVE GRAIN DEVIATION...''F6.1,
9AVERAGE GRAIN MOISTURE(PERCENT)='F6.1,'AVERAGE DETERIORATION...''F6.1,
15 CONTINUE

100 FORMAT(' *14x1x,F8.1,12x,2x,4x1x,F6.0,1x,F7.0,F5-1.1x,F4-1.1x,3F5-1.1x"

** RETURN

END

SUBROUTINE VANCE

COMMON/GRNORY/GRNHAR(6,100,3),FALWTH,150.3,STORGR(6,20,7)
*IPRT,SUPHET(6,2>,PACFAC,10ATD<150.3),FINSH,OVRFIL,FMTA,FMTM,
*BNB,NY,1DIAX,IFANDM,LAYER,BPS12,MAXLAY,DEPLOY,PH1PRINT

C

DIMENSION T(21),H(21)

COMMON/EDZ/C.GC,T.C1.HC,DELL,IRW,MC1,R,OFAN,TIJ

EXTERNAL EQZERO

A:RDRY=HEAADD/FALWTH(lDAY.I)

CFM=CFMSF/(BIN(NB,2)/1.245)

DRMTBU=47.32

HUMKK = FALHTH<1DAY.31

ABSTEM=460.*AIRDRY

ATMP=14.696

DT=24

VAPPRE=HUMKK *ATMP/(HUMKK +.625)

DENAIR=144.-(ATMP-VAPPRE)/(.5335*ABSTEM)

R = DRMTBU /(CFM $ 61.0 *DT *DENAIR *MAXLAY)

RATMAX=35CHRGRN/BULAY

IF(RATMAX.GT.1.0)RATMAX-1.0

IF(RATMAX.LT.0.5)RATMAX-.05

OFAN = 0

T(1)=AIRDRY

H(1)=HUMKK

RH = RHS(HUMKK, AIRDRY )

IFIRH=GE.1) RH = .99

RENC = SOlT(-.75*RH+.75)

OD LOOP #0# IS THE BEGINNING OF THE LAYER ANALYSIS.

DO 40 I = 1, LAYER

IJ=1

IFJ.EQ.LAYER)R=R*RATMAX

C=(( .35*.00851*STORGR(NB,1,2))*h)/(1.-STORGR(N8,1*2)/100.)

N = 0

HF=HUMKK

DELL=(1094.-.57*TI)4.35 + EXP(-28.25 * STORGR(NB,1,3)/100.0)

C

WHEN IRW = 0 DRYING

M = 0

WHEN IRW = 1 REWETTING

N = 0

WHEN IRW = 2 HYSTERESIS

IRW = 0

N = 0

REHC = RHS(H(1),TI)

C

WHEN IRW = 0 DRYING

M = 0

WHEN IRW = 1 REWETTING

N = 0

WHEN IRW = 2 HYSTERESIS

IRW = 0

N = 0

REHC = RHS(H(1),TI)
IRW = 2
GO TO 198
199 CONTINUE
IRW = 1
200 CONTINUE
IF(IRW.EQ.1) GO TO 1201
AA = H(I)
BB = H(I) + .001
GO TO 1202
1201 CONTINUE
RB = H(I)
AA = H(I) - .001
1202 CONTINUE
GC1 = STORGR(NB,1,1)
TC1 = T(I)
HC1 = H(I)
DNC1 = STORGR(NB,1,3)
CALL ZEROUT(AA, RB, +000005, EQZERU)
HF = (AA + BB) / 2.0
XMI = STORGR(NB,1,3) - 100*(HF - H(I)) / 8
T(IJ) = (CSTORGR(NB,1,1) + .24*T(I) + .45*H(I)*T(I) + QFAN
*((HF-H(I))*(1060.8+32-STORGR(NB,1,1)+C(BL)))/(1.24+.45*HF*C
 IF THE THIN LAYER EQUATION IS BYPASSED, GO TO 60 FROM HERE.
60 CONTINUE
C MI = ABS(STORGR(NB,1,3)-XMI)
IF(CMI.LT.0001) GO TO 60
XM C = STORGR(NB,1,3)
CALLTHLVLTC(XMC,T(I),H(1),DT,STORGR(NB,1,1),KAD,RAI,CMI,TXI,TFI+1)
C I,RAI,RAI
CMI = ABS(STORGR(NB,1,3)-XM C)
IF(CMI.LT.;CM2) GO TO 60
XM C = XM C
HF = H(I)-001*HH(STORGR(NB,1,3)-XM C)
198 CONTINUE
T(IJ) = (CSTORGR(NB,1,1) + .24*T(I) + .45*H(I)*T(I) + QFAN
*=(H(I))*(1060.8+32-STORGR(NB,1,1)+C(BL)))/(1.24+.45*HF*C)
60 CONTINUE
STORGR(NB,1,3) = XMI
STORGR(NB,1,2) = (100+STORGR(NB,1,3))/(100+STORGR(NB,1,3))
STORGR(NB,1,1) = T(II)
H(I,J) = HF
STORGR(NB,1,6) = STORGR(NB,1,6) + (DT/230.)/
* (SAFE(STORGR(NB,1,1),STORGR(NB,1,2)))
STORGR(NB,1,6) = STORGR(NB,1,6) + (EXP(0.06*STORGR(NB,1,6)-1.1)+.01029
* STORGR(NB,1,6)
40 CONTINUE
FANMR5=FANHRS+DT
DAVENG=DT*(7457*(HIN(NB,3)+.05)+.0176*SUPHE7(NB,1))
CUMKH=CUMKH+DAVEN
C LOGIC FOR BIN SHUT DOWN
C
GRSTA=0.0
GRSTM=0.0
DC 310 LAYER
GRSTA=GRSTA+STORGR(NB,1,2)/FLGAT(LAYER)
310 IF(STORGR(NB,1,2).GT.GRSTM)GRSTM=STORGR(NB,1,2)
IF(FDAY.EQ.100) IFINSH=1
IF(IFINSH.EQ.11) GO TO 300
IF(IFGMRSTA.GT.FMTA.OR.GRSTM.GT.FMTM) RETURN
CALL FINPRT(1)
IFAN0N = 0
RETURN
300 IF(I0AY.EQ.100) GO TO 350
IF(G&MSTA.LT.FMTA.AND.G&STMA.LT.FMTM) GO TO 300
IF(I0AY.EQ.150) GO TO 360
IF(I0AY.LT.69.AND.IDAY.GT.100) RETURN
763
IF(GRMSTA.LT.FMTA.AND.G&STM.LT.FMTM) GO TO 360
764
IF(IOAY.EQ.150) GO TO 360
766
IF(IOAY.LT.65) RETURN
768
IF(STORGR(N6+LAYER* 1).LT.18.*GO TO 350
769
IF(STORGR(N6,LAYER,2).GT.25.)RETURN
787
IF(STORGR(N6,LAYER,1).LT.15.)GO TO 350
791
764
350 IFAN0N=0
STRTHM=105+100-IDAY**24.*
IF(LPR%NT.GE.O) CALL PRINT
CALL FINPRT(1)
DO 355 :=&.LAYER
STORGR(N6+LAYER*1+6)= (STRTIM**230.0)*
*(SAFES(STORGR(N6,1)*1.1*-STORGR(N6,1,2)))*
STORGR(N6,1,5)=.0884*(EXP(.006*STORGR(N6,1,6))-1.)
**.00102*STORGR(N6,1,6)
355 CONTINUE
794
795
796
797
798
799
800
801
END
C
C FUNCTION SAFES(T,WB)
W=WB
IF(W .LE. 1)M=W*100.
DM=1.0
TR=230.0
D8=W/(100.-W)*100.
XMM=.103*(EXP(455./D8*1.53)-.00845*D8+1.558)
10 XMT=226.75*EXP(-.081*T)
GOTO 70
20 IF(*)=19.*30,30,40
30 *=19.
40 IF(W-28.)60,60,50
50 *=28.
60 XMT=32.3*EXP(-3.48*T/60.)+(W-19.)*.01*EXP(.61*(T-60.)/60.)
70 SAFES=TR*XMM*XMT*DM
RETURN
END
C
C FUNCTION E0ZERO 02/27/76
FUNCTION E0ZERO(HF)
COMMON/E0z/C,G,T,H,0£LL1R*.DM,R,OFAN,TIJ
XM1 B DM = 100.0
#(HF - H)/ R
TIJ = .24 + 1.0 + .45*HFT + OFAN
S =-((HF - H)*(1260*8 + 32.0 - 0 + DELL))/(.24 + .45*HF + C)
RETURN
END
C
IF(XMI.LT.001) XHI = .001
GO TO 1190
ERH = 1. - EXP(-3.02e-9*(TIJ + 50.0) * XM(1,1))
GO TO 1191
1190 CONTINUE
ERH = 1. - EXP(-1.49e-4*(TIJ) + 50.0) * XM(1,1,1,2)
1191 CONTINUE
RHSS = RHS(HF,TIJ)
ERZERO = ERH - RHSS
RETURN
END

C #**************$***$$**$****$***$$**$*****************$******#$$ dbl
FUNCTION PSOG (00)
DOUBLE PRECISION R.A.8,C,D,E.F.G
REAL MS DEXP
DATA P*A,B,C#D,E,F.G/.3206182232004,-.2740552583614
26006,.54189607
1F(DB-49.169)
1,2,2
PSDB = EXP(23.3924-11286.64 /0B-.46057*ALCG(08))
RETURN
2 PS08sR*DEXP((AfD8*(8*08#(C»08*(Df08*E))))/(OB$(F-G*OB)))
RETURN
END

C #$*$$****$***$****#**#***$*»*$$$$*$#$$$$$*$$**#$*$$****»***,***
C RHS SUBPROGRAM
FUNCTION RHS(H, TS)
T = TS • 459.69
PS = PSOB<T) (14.696*H/(H**0.6219))/ PS
RETURN
END

C ***$*$#*$#$$$$#$$$*$#$#****$*»***$$******$*$****$*********$*#$*»
C SUBROUTINE ZEROUT
SUBROUTINE ZEROUT(A, B, EPS, FUNC)
C UPDATE 8/17/76. RANGE SELECTOR ADDED.
REAL I, M
IC = 0
0 = B - A
20 CONTINUE
IF(IC.GE.20) GO TO 30
FA = FUNC(A)
FB = FUNC(B)
FC = FA
C = A
IF(SIGN( 1. ,FB) •N£.S1GN( 1 . «FO ) GJ TO 1
IC = IC + 1
IF(ABS(FA).GT.0ABS(FB)) GO TO 21
B = A + (2*EPS)
A = A - 0
GO TO 20
30 CONTINUE
WRITE(6,100) IC, A, B, FA, FU
100 FORMAT(1X,*ZEROUT CANT FIND A RANGE IN *JLZ* ITERATIONS. LIMITS
**=*2F12.6** FUNCTION VALUES = *2F12.6)
RETURN
21 CONTINUE
A = B - (2*EPS)
B = B + D
RETURN
GO TO 20
1 IF(ABS(FC) - ABS(FB)) 2, 3, 3
2 C = B 201
3 C = A 202
4 FC = FB 203
5 FB = FA 204
6 FA = FC 205
7 IF(ABS(C - B) - 2. * EPS) 12, 12, 4
8 M = (C + B) / 2.0 209
9 IF(ABS(C - B) - 2. * cPS) 12. 12* 4 90d
10 i = -1 + 0 910
11 IF(F/>F< = 0) CALL OVERFLdREGI 912
12 CALL OVERFLdREGI 914
13 IF (IREG.NE.2I GO TO 7 91S
14 I = (B - I) * (C - I) 916
15 I = -I • B 918
16 IF(ABS(B - II- EPS I 9» 10# 10 920
17 I = SIGNd.,(C - Bll » EPS f 8 921
18 A = 8 922
19 8=1 923
20 FA = FB 924
21 FB = FUNC(BI 925
22 IF(SIGN(1«»FB1 = SIGN d. .FBI I 8 = C 932
23 RETURN 933
24 END 934

C SUBROUTINE THLYLT(XMC,TH,MA,DELT,XMD,RH,XME,TM0,I,RHA,IHV)
27 DIMENSION TGUESS(SO)
28 DATA TGUESS/50!
29 RH = RHA 30
30 XMC=SORT((-ALOG11.-RHII/(1.0000382*1TH*50.)) 31
32 IF(XMC*LT»XMCI GO TO 12 33
34 WRITE(6,1090) XMC, XME, IH, TH, RM 35
1090 FORMAT(IX,'POSSIBLE ERROR IN THLYLT, VARIABLES * #2P8.4,**:5,ZFd.^l
36 12 IF(XMD,LT«XHCI GCJ TO 13 37
38 TXMD=XMO 38
39 GO TO 15 30
13 TXMD=XMC 39
15 DELM=TXMD-XME 40
41 XMC=(XMC-XME)/DELM

C EQUATIONS TO FIND MOISTURE CONTENT BY M.A. SABBAB
42 RSO=RH$RH 43
44 X=0.124 5-0.224RH*0.002j*RH*TH-0.000058#TH 45
46 K=0 46
47 T1=TGUESS(11 48
C CHECK IF DERIVATIVE IS VERY LARGE...IF I IS ASSIGN 12=0.0 49
50
IF(XMR.LT.999) GO TO 102
T2=0.0
GOTO 104
102 U=ALOG(-ALOG(XMR))

NEWTON-RAPHSON TECHNIQUE TO FIND EQUIVALENT TIME

103 Z1=X*T1**Y-.664*ALOG(T1)*U
Z2=X*T1**Y*(Y-1.1-.664/T1
T2=T1-Z1/Z2
K=K+1
EPS=ABS(T2-T1)
IF(T2.LT.0.01) T2=0.0010
T1=T2
IF(K.LT.20) GO TO 300
WRITE(6,150) K
WRITE(6,301)T2, T1, Z1, Z2, X, Y, U, XMR

STOP
300 CONTINUE
150 FORMAT(33HTHE METHOD HAS NOT CONVERGED IN * 12.11M ITERATIONS)
IF(EPS.GT.0.01.AND.Z1.GT.0.01) GO TO 103
ADD DELT TO EQUIVALENT TIME, SOLVE FOR NEW M AND RETURN
104 T2=T2#DELT
T=DELT#EXP(-EXP(-X*T2**Y)*T2**.664)*XMR
RETURN
END
SECTION III:
MANAGEMENT STRATEGIES FOR CORN
PRODUCTION AND LOW-TEMPERATURE DRYING
INTRODUCTION

Computer models CORNSIM and FALDRY are used to conduct a comprehensive simulation study of corn production and low-temperature drying for Central Iowa conditions. CORNSIM simulates the cropping system from planting through harvest. Given a specific management strategy, machinery capacity, and cropping season, CORNSIM simulates planting, crop development, yield, and harvesting. CORNSIM was developed to provide the simulated flow of harvested grain. FALDRY receives the simulated harvest data and carries the crop through drying to storage. FALDRY simulates a system of low-temperature corn drying bins. FALDRY inputs include bin specifications, weather data, and the incoming flow of harvested grain. FALDRY was developed to predict the success or failure of a low-temperature corn drying system and the amount of electrical energy it would consume. This study addressed three major objectives:

1. Determine the relative benefits of additional fan power versus the use of supplement heat to enhance the performance of a low-temperature drying system.

2. Test the feasibility of designing a low-temperature drying system to match the corn harvesting capacity of a typical Central Iowa farming enterprise.

3. Develop the optimum daily filling strategy and design recommendations for a low-temperature corn drying system for Central Iowa.
The literature review is limited to examining how existing low-temperature grain drying models have been used to determine optimum management and design strategies or the feasibility of alternate energy sources and automatic control devices. A detailed literature review of the actual drying models is reported in Section II.

The development of digital low-temperature grain drying models was first reported in the late 1960s. Initial results indicated that drying with natural (unheated) air might be feasible. One of the first optimization studies was reported by Morey and Peart (1969). They determined the optimum fan power and grain depth for a natural air corn drying system assuming constant weather conditions and grain moisture for both single-fill and layer-fill systems.

For a single-fill bin, the optimum depth was approximately 2.5 meters (8 feet), and fan power of roughly 0.05 kilowatts per cubic meter (2 horsepower per thousand bushels).1 Interestingly, layer-filling was significantly different from a single-fill; the depth increased about 50 percent, the fan power was reduced 50 percent, and the drying cost was

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1 Note - The following definitions and assumptions are used throughout this paper:

- 1 t = 1 metric ton of corn = 1,000 kg of dry matter.
- 1 t = 1.65 cubic meters of corn.
- 1 bu = 1 bushel of corn = 47.32 pounds of dry matter.
- 1 bu = 1.245 cubic feet of corn.
- 1 t = 46.6 bu.
- 0.01 m³/s·m⁻³ = 0.75 cfm/bu.
- Fan power (fan size) is expressed in kilowatts, the electrical load during operation.
reduced about 20 percent. Using a purely mathematical analysis, Barre and Hamdy (1974) reported a potential of matching harvesting capacity with layer-fill, low-temperature drying system.

Building on existing research, Bloome and Shove (1972) reported on a more comprehensive study of optimizing natural air drying. Their results followed the same trends as the results of Morey and Peart (1969). They suggested two methods to handle grain above 24 percent MCWB that could relieve the requirements for shallow grain depths and high fan power: One, a layer-filling procedure; or two, use of a high-temperature dryer to reduce the grain moisture before it entered the low-temperature system.

Beginning in 1974, the Federal Government funded research to study the feasibility of using solar energy as a supplemental heat source for low-temperature grain drying (Pierce and Thompson, 1976; Bakker-Arkema et al., 1977; and Morey et al., 1977). Three different grain drying simulation models were developed by the researchers. Using the models and weather data from several locations throughout the Corn Belt, they tested the feasibility of using solar energy as a supplemental heat source for low-temperature corn drying. There were minor differences in published conclusions, but the results showed:

1. The models used were accurate enough to be useful predictors of moisture content changes, energy used, and resulting quality changes during drying.

2. For most locations, there were 1 or 2 years out of 10 that required a considerably higher airflow rate than the other years.
This increase was usually caused by unseasonably warm temperatures during the initial drying period.

3. The rate of airflow is the most critical design parameter in the design of low-temperature drying bins. Minimum safe airflow rate was most significantly affected by the initial moisture content of the grain; but also important was the date of filling and geographic location:
   a. Between 20 and 25 percent grain moisture, the minimum airflow rate approximately doubled for each 2% MCWB increase in grain moisture.
   b. To start drying earlier in the season required higher airflow rates to meet the grain quality criterion of not more than 0.5 percent dry matter loss.
   c. Across the Corn Belt, the required drying time increased from southern to northern areas.
   d. Across the Corn Belt, the minimum airflow rate increased from cool dry North Dakota to warmer more humid areas of Central Indiana and Ohio.

4. Assuming equal amounts of supplemental heat, there was no significant difference between intermittent solar or constant heat sources.

5. The addition of supplemental heat slightly reduced the hours of fan operation, but the fan energy savings was not sufficient to justify solar collectors or supplemental electric heat.

6. The addition of supplemental heat did not significantly reduce
the dry-matter-decomposition in the top of the grain bin.

7. The minimum required airflow rate was not significantly reduced by adding supplemental heat above the 1.1°C temperature rise assumed across the fan. The exceptions were Central Indiana and Ohio, where an additional 1.7°C did reduce the required airflow rate.

8. The addition of supplemental heat usually resulted in a significant increase of over-dried grain.

9. Economic analyses showed the benefits of supplemental heat improve for initial filling moistures below 22 percent and/or later filling dates.

Pfost et al. (1977) reported on a simulation study of six different fan management strategies involving the use of time clocks and humidistats. Because all the simulations were run using exactly 20 days (Sept. 23-Oct. 12, 1974) of weather data for Manhattan, Kansas, it is difficult to draw conclusions for the Corn Belt; but the results indicate that strategies to reduce fan energy increase drying time and substantially increase dry-matter-decomposition.

Morey et al. (1978) studied a variety of fan management strategies for single-fill, layer-fill, and stirred-bin drying systems using several years of weather data from three Corn Belt locations. They reported the following conclusions:

1. Continuous fan operation, under an appropriate fall shut-off and spring start-up procedure, was preferable to management strategies which involved turning off the drying fan based on relative humidity, temperature, or a time clock.
2. Layer-filling the bin over a period of days allowed an increase in allowable initial moisture content of up to 3 percentage points, depending on the schedule, when compared to a single-fill procedure.

3. Increasing airflow to $0.027 \text{ m}^3/\text{s} \cdot \text{ m}^3$ for a full bin allowed the initial moisture content to be increased to as much as 27 percent on a layer filling schedule. Fan power and depth restrictions may limit this application.

4. Stirring offered potential advantages for reducing maximum dry-matter-decomposition and minimizes overdrying. Stirring at 7- to 14-day intervals appears to be preferable to continuous stirring. Investment costs for stirring devices for in-storage drying systems should be carefully analyzed.

Pierce and Thompson (1978a, 1978b) expanded their low-temperature corn drying simulation studies to cover most of the corn growing areas in the United States. They address the questions of minimum required airflow rates, economic feasibility of supplemental heat, the potential of layer drying, and overdrying. They reported the following conclusions:

1. Airflow was the most critical design factor. Using their minimum required airflow rates, low-temperature drying is possible in all major U.S. corn producing areas.

2. The effect of supplemental heat varies with location. Assuming $1.1^\circ \text{C}$ heat rise across the fan, an additional $1.7^\circ \text{C}$ is economically feasible only for Indiana conditions.

3. Layer-filling makes it possible to accept higher initial grain moisture without increasing the minimum required airflow rates.

4. Overdrying was a significant problem when supplemental heat was added. Of the methods studied, only stirring alleviated over-drying without adversely affecting grain quality.

5. The pure equilibrium grain drying model overpredicted the rate of drying for relatively high airflow rates. The inclusion of a thin layer drying equation will improve the model accuracy.
SUMMARY OF CORNSIM AND FALDRY

CORNSIM is a deterministic corn production model developed to simulate crop seasons 1958 through 1975 in Central Iowa. The model is designed to function with user-specified crop acreages, machine capacities, and management strategies. CORNSIM was developed to produce simulated corn harvest data which in turn is used as input to a new low-temperature drying and storage model, FALDRY. CORNSIM is unique among corn simulation models in two respects. First, it accounts for the interactions between machine capacities, crop development, and management strategy. It predicts the planting, growth, and harvest status of a complete corn production system. Second, the major objective of CORNSIM is to predict on a daily basis both the quantity and moisture content of the harvested grain. Unlike many corn models that predict the yield response to the soil, weather, and water environment using either a regression equation or photosynthesis model, CORNSIM uses yearly recorded yield data as the starting point and adjusts the yield for planting date, frost damage, and harvest date. An objective of CORNSIM is simulation of grain moisture content from dough stage to harvest with respect to Julian date.

CORNSIM iterates with a 24-hour time base. It uses 18 data sets including date code, daily average weather conditions, field trafficability code, and cumulative growing degree units for years 1958-1975. Operating within the limitations of the given management strategy, machine capacity, and soil conditions, the model simulates the progression of the planting operation. Once the individual fields are planted, the plant growth
stage (sprouting to flowering phase) is simulated by accumulating growing degree units. Next, the ear development stage (flowering to 75 percent kernel moisture) is simulated by accumulating calendar days. Third, the maturing and dry-down stage (75 percent kernel moisture to harvest) is simulated using a five-stage regression algorithm. Each of the five equations operate within a limited moisture range and are functions of dry bulb temperature, wet bulb depression, and/or equilibrium moisture content of the grain. Finally, subject to the given limitations of machine capacity, management strategy, field trafficability, and weather, the harvesting operation is simulated concurrent with the latter part of the maturing and dry-down stage. The simulated harvested grain flow data produced by the model consist of year, Julian date, grain quantity, grain moisture, and grain temperature. CORNSIM results for the years 1967-1975 have been validated against historical data published by the Iowa Crop and Livestock Reporting Service.

FALDRY is a deterministic low-temperature grain drying model designed to simulate a complete farm drying system. The model functions with user-specified grain bins and drying fans. FALDRY is unique among grain drying models because it simulates the performance of a drying system of circular steel bins with perforated floors and axial-flow fans rather than the generalized, dimensionless drying process. FALDRY begins simulation on September 8. During the next 100 days, FALDRY can accept grain on a daily basis at any specific quantity, moisture, and temperature. Operating from user-supplied specifications for bin dimensions, fan size, and supplemental heat capacity, FALDRY determines on a daily basis the
grain depth, airflow, static pressure, and heat rise. Functioning with 24-hour average weather data, FALDRY simulates the progress of drying. The actual grain drying portion of FALDRY is composed of a modified version of the Minnesota model (Morey et al., 1976).

The number of layers in a FALDRY bin can vary from 1 to 20 layers. A one-layer simulation can be used as an approximation of a continuously stirred bin. A 5- to 10-layer simulation is adequate for analysis of single-fill, full-bin systems. Twenty-layer simulations are particularly useful for the analysis of layer-filled bins. The top layer of grain need not be full because FALDRY is able to simulate a partial layer; thus, the model can accept grain in any quantity. Once the bin is full, FALDRY informs the user of the additional grain but does not include it in the simulation. Each call to FALDRY is designed to simulate a one- to six-bin system with complete flexibility in filling strategy. FALDRY is designed to function with continuous fan and heater operation. If drying is not completed during the fall, a fall shutdown procedure is followed. Drying resumes on the first of April. (See Figure 1 for details of the fan management strategy.) FALDRY simulates the fall and spring drying seasons. Winter and summer aeration cycles are not included.

More detailed technical descriptions, program listings, and user's manuals for CORNSIM and FALDRY are reported in Sections I and II, respectively.
FALDRY - FAN MANAGEMENT STRATEGY

1. The fan starts as soon as the first bushel of corn enters the bin and runs continuously until the user specifies he has finished filling the bin at which time the fall and final shutdown logic takes control. If final shutdown conditions are met before the user indicates that filling is complete, the fan temporarily shuts down until more corn enters the bin.

2. Final shutdown of the fan occurs as soon as the average corn moisture is less than 14.5% MCWB and the maximum corn moisture in all layers is less than 15.5% MCWB, or the date is May 20.

3. If conditions for final shutdown do not occur during the fall drying season, the fall shutdown criteria will turn off the fan and restart it on April 1. Fall shutdown occurs when any one of four conditions are met:
   
   a. The date is after November 15, and the top layer of grain is less than 30°F and less than 18% MCWB.
   
   b. The date is after December 1 and the top layer of grain is less than 25°F and less than 20% MCWB.
   
   c. The date is after December 1 and the top layer of grain is less than 20°F.
   
   d. The date is December 16.

Winter dry matter deterioration is predicted based on fall shutdown conditions. The effects of winter operation on grain moisture and temperature are not included. Electrical energy for winter aeration is not tabulated.

Figure 1. Fan management strategy for the FALDRY model
RELATIVE BENEFIT OF ADDING SUPPLEMENTAL HEAT  
OR ADDITIONAL FAN POWER

In spite of a significant amount of research on the merits of supplemental heat, there is still a need for additional investigation. Beginning with a simplified psychrometric analysis and progressing through a complete simulation study using FALDRY, this section evaluates the relative merits of supplemental heat and additional fan power.

Simplified Psychrometric Analysis

Figure 2 outlines a sample problem to illustrate the performance of a typical low-temperature drying bin. Since the grain below the initial drying front in a low-temperature drying bin approaches equilibrium with the drying air, it is important to understand the difference between the rate of moisture removal and the drying rate (the movement of the initial drying front). Ideally, we would like to maintain an equilibrium moisture of 14 to 15.5% MCWB while maximizing the drying rate. Increasing the rate of moisture removal is not necessarily productive, especially if significant overdrying occurs.

Using the results of the sample problem as base conditions for rate of water removal and drying rate, Table 1 was developed to illustrate the relative effects of changing airflow and heat rise. Each percentage increase of airflow resulted in a comparable increase in both water removal and drying rate, whereas a .56°C (1°F) increase in heat rise resulted in an 8-percent increase in water removal but only a 4-percent increase in drying rate. The difference in rate increases is due to the lower
Sample Problem

Given:
- Bin Capacity 352.6 cubic meters (10,000 bushels)
- Grain Depth 5.2 meters (17 feet)
- Airflow Rate .0134 m³/s·m³ (1 cfm/bu)
- Initial Grain Moisture 22% MCWB

Assumptions:
- Ambient Air Conditions
  - Dry Bulb 7.2°C (45°F)
  - Wet Bulb 4.4°C (40°F)
- Heat Rise Across the Fan 1.1°C (2°F)
- Drying air picks up 80% of its potential moisture-absorbing capacity

Calculations:

Rate of Water Removal

a. Compute Mass of Airflow
   \[ \text{Ventilation} \times \text{Bin Capacity} \times \text{Air Density} = 5.9 \text{ kg/sec} (780 \text{ lb/min}) \]

b. Compute Water Removed per Unit of Dry Air
   \[ \text{Saturated Humidity} - \text{Initial Humidity} = 0.00108 \text{ kg Water/kg Dry Air} \]

c. Compute Rate of Water Removal
   \[ \text{Water Mass Removal} \times \text{Conversion Factor} = 22.9 \text{ kg/hour} (50.5 \text{ lb/hour}) \]

Rate of Grain Drying

a. Compute the Equilibrium Moisture of the Grain
   14.0% MCWB

b. Compute the Mass of Water Removed per Unit of Grain
   \[ \text{Total Weight at 22% MCWB} - \text{Weight at 14% MCWB} = 119 \text{ kg Water/metric ton} (5.6 \text{ lb/bu}) \]

c. Compute Rate of Drying
   \[ \text{Rate of Water Removed per Unit of Grain} = 0.19 \text{ metric ton/hr} (9.0 \text{ bu/hr}) \]

Figure 2. Simplified psychrometric analysis of a low-temperature drying bin
<table>
<thead>
<tr>
<th>Heat Rise of Ambient Air °C (°F)</th>
<th>Equilibrium Grain Moisture % MCWB</th>
<th>Percent Change from Base Water Removal Rate - Upper Number</th>
<th>Percent Change from Base Drying Rate - Lower Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 (0.0)</td>
<td>14.8</td>
<td>-33</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-26 - 8</td>
<td>67</td>
</tr>
<tr>
<td>0.56 (1.0)</td>
<td>14.4</td>
<td>-27 - 8</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-23 - 4</td>
<td>73</td>
</tr>
<tr>
<td>1.11 (2.0)</td>
<td>14.0</td>
<td>-20 0.0</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-20 0.0</td>
<td>80</td>
</tr>
<tr>
<td>1.67 (3.0)</td>
<td>13.6</td>
<td>-13 08</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-17 04</td>
<td>87</td>
</tr>
<tr>
<td>2.22 (4.0)</td>
<td>13.3</td>
<td>- 7 16</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-14 08</td>
<td>94</td>
</tr>
<tr>
<td>2.78 (5.0)</td>
<td>12.9</td>
<td>0 25</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-11 11</td>
<td>101</td>
</tr>
<tr>
<td>3.33 (6.0)</td>
<td>12.6</td>
<td>7 33</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- 8 15</td>
<td>108</td>
</tr>
<tr>
<td>3.89 (7.0)</td>
<td>12.3</td>
<td>13 42</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 19</td>
<td>131</td>
</tr>
<tr>
<td>4.44 (8.0)</td>
<td>12.0</td>
<td>20 50</td>
<td>183</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 23</td>
<td>139</td>
</tr>
</tbody>
</table>
equilibrium moisture when supplemental heat is added and the resultant overdrying. A 20-percent increase in airflow produces the same increase in water removal as a 1.4°C (2.5°F) heat rise and the same increase in drying rate as a 2.8°C (5°F) heat rise. These effects are significantly different from those obtained with drying systems where stirring equipment or continuous flow metering devices can be used to control final grain moisture.

Simulation of Drying Front Movement

Increasing the fan power on a bin does more than increase the airflow. It also increases the temperature rise across the fan. Figure 3 shows the fan power, airflow, and temperature rise relationships for a 9.14 meter (30-feet) diameter bin filled with 5.18 meter (17 feet) of grain using the axial-flow fan model in FALDRY and a 1.5 pack factor. Both the temperature rise across the fan and the airflow per unit of grain are sensitive to the fan power to grain ratio, fan efficiency, grain depth, and pack factor. Section II reported on these relationships.

The effect of adding fan capacity or supplemental heat to increase drying rate was further evaluated in a three-bin simulation. One bin was equipped with a 7-kW fan, the second bin with a 7-kW fan and 8.5-kW heater, and the third bin with a 14-kW fan. Other assumptions for the three bins were as follows:

1. 28 yr average Des Moines weather data
2. 9.14 meter (30-feet) diameter bins
3. 5.33 meter (17.5 feet) of grain
Figure 3. Fan-bin performance characteristics for 9.14 m (30 ft) diameter bin with 5.18 m (17 ft) of corn depth using the FALDRY fan model and a 1.5 pack factor
4. Initial grain moisture 22% MCWB
5. Mid-October filling
6. Airflow and temperature rises as computed by FALDRY using 1.5 pack factor.

The performance of the three systems is outlined in Table 2. Figure 4 illustrates the progress of the initial drying zones and the moisture profiles in the bins during drying. Bin 1 completed drying after 8 weeks with an average grain moisture of 14.5% MCWB and a total electrical consumption of 9,264 kilowatt-hours. Bin 2 required a little over 6 weeks to finish drying with an average grain moisture of 13.2% MCWB and a total electrical consumption of 15,945 kilowatt-hours. Bin 3 completed drying in a little less than 5 weeks with an average grain moisture of 13.7% MCWB and a total electrical consumption of 10,780 kilowatt-hours. These results indicate that the drying rate can be more effectively increased by adding fan capacity than by adding supplemental heat.

Table 2. Fan power, airflow rate, and temperature rise for three bin systems

<table>
<thead>
<tr>
<th>Bin No.</th>
<th>Fan size (kW)</th>
<th>Heater size (kW)</th>
<th>Temperature rise</th>
<th>Airflow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(°C) (°F)</td>
<td>(m³/s·m³) (cfm/bu)</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>--</td>
<td>1.3 (2.3)</td>
<td>0.013 (0.94)</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>8.5</td>
<td>2.8 (5.0)</td>
<td>0.013 (0.94)</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>--</td>
<td>1.8 (3.3)</td>
<td>0.017 (1.28)</td>
</tr>
</tbody>
</table>
Figure 4. Simulated grain moisture profiles for the three hypothetical bins using 28-year average Des Moines, Iowa, weather data.
Computer Analysis of Full-Bin Systems

Several factors, in addition to drying rate, are critical to the overall performance of a low-temperature drying system, i.e., the resulting grain quality, the total energy used per unit of grain, and the ability of the system to successfully dry grain in the problem years. FALDRY was used to simulate approximately 200 bin-years for a variety of fan and heater combinations.

The following assumptions were used for the "standard" bin:

- Bin Diameter: 9.14 meters (30 feet)
- Grain Depth: 5.33 meters (17.5 feet)
- Pack Factor: 1.5
- Filling Date: October 15
- Initial Grain Moisture: 22% MCWB
- Weather Data: 18 years from Des Moines, Iowa

Table 3 summarizes the results of the full-bin study. Figures 5, 6, and 7 graphically illustrate the superior performance of "fan power only" systems over equivalent energy combinations of "fan and heater" systems. Not once in all the simulation runs did a "fan and heater" combination equal or exceed the performance of "fan power only", comparing equal energy input systems.

Appendix A reports the results from an additional 900 simulated drying runs. In addition to varying the fan/heater systems, the bins were layer-filled using 18 years of CORNSTM data for three different management strategies. The results only reinforced the above findings about the advantage of additional fan capacity over electric supplemental heat.
Table 3. Grain drying performance of several fan and heater combinations

<table>
<thead>
<tr>
<th>Fan size (kW)</th>
<th>Heater size (kW)</th>
<th>Total power (kW)</th>
<th>Drying time (hours)</th>
<th>Total drying energy (kWh/t)</th>
<th>Maximum dry matter loss (%)</th>
<th>Number of failures (18 possible)</th>
<th>Number of spring finishes</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.4</td>
<td>-</td>
<td>4.4</td>
<td>1877</td>
<td>38.7</td>
<td>1.36</td>
<td>1.15</td>
<td>15</td>
</tr>
<tr>
<td>4.4</td>
<td>8.8</td>
<td>13.2</td>
<td>1536</td>
<td>95.2</td>
<td>2.04</td>
<td>.97</td>
<td>2.04</td>
</tr>
<tr>
<td>8.8</td>
<td>-</td>
<td>8.8</td>
<td>1224</td>
<td>50.3</td>
<td>1.08</td>
<td>.68</td>
<td>.64</td>
</tr>
<tr>
<td>8.8</td>
<td>4.4</td>
<td>13.2</td>
<td>1085</td>
<td>67.1</td>
<td>1.44</td>
<td>.66</td>
<td>.64</td>
</tr>
<tr>
<td>8.8</td>
<td>8.8</td>
<td>17.6</td>
<td>983</td>
<td>81.1</td>
<td>1.74</td>
<td>.64</td>
<td>.64</td>
</tr>
<tr>
<td>8.8</td>
<td>17.5</td>
<td>26.3</td>
<td>831</td>
<td>102.5</td>
<td>2.20</td>
<td>.67</td>
<td>.62</td>
</tr>
<tr>
<td>13.2</td>
<td>-</td>
<td>13.2</td>
<td>929</td>
<td>57.3</td>
<td>1.23</td>
<td>.57</td>
<td>.54</td>
</tr>
<tr>
<td>13.2</td>
<td>4.4</td>
<td>17.6</td>
<td>845</td>
<td>69.4</td>
<td>1.49</td>
<td>.57</td>
<td>.54</td>
</tr>
<tr>
<td>13.2</td>
<td>13.2</td>
<td>26.4</td>
<td>726</td>
<td>89.5</td>
<td>1.92</td>
<td>.57</td>
<td>.54</td>
</tr>
<tr>
<td>17.5</td>
<td>-</td>
<td>17.5</td>
<td>769</td>
<td>63.4</td>
<td>1.36</td>
<td>.53</td>
<td>.50</td>
</tr>
<tr>
<td>26.3</td>
<td>-</td>
<td>26.3</td>
<td>613</td>
<td>75.5</td>
<td>1.62</td>
<td>.50</td>
<td>.47</td>
</tr>
</tbody>
</table>

Note: Average over 18 years of simulated results.

b Dry matter loss exceeded .5 percent.
Figure 5. Drying time versus total electrical power supplied to the "standard" bin.
Figure 6. Drying energy versus total electrical power supplied to the "standard" bin.
Figure 7. Maximum dry matter loss versus total electrical power supplied to the "standard" bin.
Conclusions

1. An increase in airflow results in an equal increase in moisture removal and drying front movement. But an increase in heat rise results in only half the increase in drying front movement as the increase in moisture removal.

2. Assuming grain depths of 5 to 6 meters, both the heat rise across the fan and the airflow are sensitive to changes in the fan-power-to-grain ratio. A \(0.013 \, \text{m}^3/\text{s} \cdot \text{m}^3\) (1 cfm/bu) airflow would accompany about a 2 to 3°F heat rise. Increasing fan power enough to produce a 50 percent increase in airflow would double the heat rise.

3. Additional fan power significantly reduces both drying time and grain deterioration whereas adding supplemental heat is only 50 percent as effective at reducing drying time and has little effect on the final grain quality.

4. The most efficient method of using electrical energy to increase drying rate, improve the probability of drying in the fall, and reduce grain deterioration is to increase fan power.

5. The energy efficiency of low-temperature drying can be improved by the design and use of high-performance fans. This would result in increased quantity of ambient air supplied by the fan per unit of electrical energy consumed.

\[\text{Based on the conclusions, all future low-temperature drying systems discussed in this paper will be natural air drying systems (low-temperature drying systems with no supplement heat added).}\]
6. It is presently not practical to design full-bin systems with grain depth of 5 meters or more that can successfully dry corn above 22% MCWB every year.
THE EFFECT OF CORN PRODUCTION STRATEGIES
ON A LOW-TEMPERATURE DRYING SYSTEM

Many consider low-temperature drying systems to be practical only for limited applications because of relatively low drying rate and the deterioration rate of high-moisture corn. Some have promoted the combination drying systems that use a high-temperature system to dry corn to approximately 20 percent followed by a low-temperature system to finish drying to safe storage moisture. Others promote full-bin, low-temperature drying for late in the harvest season after the moisture has dropped to 31 percent or less. These bins are used to complement an existing drying system on a medium-size farm or as a complete system on small farms that use custom harvest. Few have considered the feasibility of designing a layer-filled, low-temperature system to match the harvest capacity of a typical Midwest farm.

There are several reasons that a layer-filling system may be practical:

1. Most farmers harvest grain over a 3- to 5-week period.
2. An in-storage drying system does not have to dry grain as fast as it is harvested. It needs only to bring the grain to a safe storage moisture before unacceptable deterioration occurs.
3. As long as grain quality can be maintained, the slower methods of drying offer substantial energy savings.
4. For layer-filled bins, the airflow per total bin capacity is not the critical parameter. Rather, the transient ratio of airflow
per unit of wet grain is the determining factor of successful
drying.

Outline of CORNSIM Runs

Soon after the original development of low-temperature drying mod­
els, researchers realized the necessity of using several years of daily
weather data to study the feasibility of natural air drying. Likewise,
there exists an obvious relationship between the weather and the physio­
logical development of the grain in the field. The same ambient air
conditions that speed natural air drying in a bin result in rapid field
drydown. Also, weather that produces limited field trafficability likely
results in slower drying in a natural air bin. Thus, a realistic low­
temperature drying study should have grain inputs sensitive to the weather
of the year being simulated. This would be especially true for a layer­
filling study.

The corn production model CORNSIM was specifically designed to simu­
late the harvested grain flow for user-defined management strategies for
Central Iowa conditions. Table 4 outlines a "base" management strategy
considered to be typical of medium-size Central Iowa farms. The simu­
lated progress of the planting, silking, maturing, and harvesting of the
crop under "base" assumptions compares closely with actual observed
data. Table 5 outlines several alternate management strategies that
allow one to study the effects of varying hybrid selection, planting
methods, and harvesting strategies.

Table 6 outlines the management inputs and gives summary results of
Table 4. Base management strategy

<table>
<thead>
<tr>
<th>Area of corn production</th>
<th>- 121.4 hectare (300 acres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum field days for tillage before planting may begin</td>
<td>- 15</td>
</tr>
<tr>
<td>Earliest possible day planting may begin</td>
<td>- April 26</td>
</tr>
<tr>
<td>Last day to plant full season corn</td>
<td>- May 14</td>
</tr>
<tr>
<td>Last day to plant medium season corn</td>
<td>- May 28</td>
</tr>
<tr>
<td>Last day to plant short season corn</td>
<td>- June 3</td>
</tr>
<tr>
<td>Effective planting rate</td>
<td>- 2.02 hectare/hr (5 Ac/hr)</td>
</tr>
<tr>
<td>Hybrid selection</td>
<td>- Full season</td>
</tr>
<tr>
<td>Effective field working time</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>- 7 hr/day</td>
</tr>
<tr>
<td>May 1-14</td>
<td>- 8 hr/day</td>
</tr>
<tr>
<td>May 15-June</td>
<td>- 9 hr/day</td>
</tr>
<tr>
<td>Fall harvest season</td>
<td>- 8 hr/day</td>
</tr>
<tr>
<td>Begin harvest as soon as the grain moisture in the field reaches</td>
<td>- 24% MCWB</td>
</tr>
<tr>
<td>Or the arrival of</td>
<td>- November 1</td>
</tr>
<tr>
<td>Grain harvesting rate equals</td>
<td>- 1.01 hectare/hr (2.5 Ac/hr)</td>
</tr>
<tr>
<td>But is limited to a maximum of</td>
<td>- 6.44 T/hr (300 bu/hr)</td>
</tr>
</tbody>
</table>
Table 5. Alternate management strategies

<table>
<thead>
<tr>
<th>PLANTING</th>
<th>Early</th>
<th>Base</th>
<th>Late</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum field days</td>
<td>8</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>First planting day</td>
<td>Apr. 19</td>
<td>Apr. 26</td>
<td>May 3</td>
</tr>
<tr>
<td>Effective field time (hours/day)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>10</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>May 1-14</td>
<td>11</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>May 15 - June</td>
<td>12</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HYBRID SELECTION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Med.</td>
<td>- All crop area planted with a medium season hybrid</td>
</tr>
<tr>
<td>Base</td>
<td>- All crop area planted with a full season hybrid</td>
</tr>
<tr>
<td>Comb.</td>
<td>- 1/3 of crop area planted with medium season hybrid first followed by the remaining 2/3 planted with full season hybrid</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HARVEST MOISTURE</th>
<th>High</th>
<th>Base</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning harvest (MCWB)</td>
<td>26%</td>
<td>24%</td>
<td>22%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HARVEST CAPACITY</th>
<th>Slow</th>
<th>Base</th>
<th>Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective field time (hours/day)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall season</td>
<td>4</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>
Table 6. CORNSIM results^  

<table>
<thead>
<tr>
<th>CORNSIM Run No.</th>
<th>Planting strategy</th>
<th>Hybrid selection</th>
<th>Harvest moisture</th>
<th>Harvest capacity</th>
<th>Average Yield</th>
<th>Average income $/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base</td>
<td>Base</td>
<td>Low</td>
<td>Base</td>
<td>799.6</td>
<td>37260</td>
</tr>
<tr>
<td>2</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>808.2</td>
<td>37660</td>
</tr>
<tr>
<td>3</td>
<td>Base</td>
<td>Base</td>
<td>High</td>
<td>Base</td>
<td>813.9</td>
<td>37930</td>
</tr>
<tr>
<td>4</td>
<td>Base</td>
<td>Med.</td>
<td>Low</td>
<td>Base</td>
<td>756.2</td>
<td>35240</td>
</tr>
<tr>
<td>5</td>
<td>Base</td>
<td>Med.</td>
<td>Base</td>
<td>Base</td>
<td>765.2</td>
<td>35660</td>
</tr>
<tr>
<td>6</td>
<td>Base</td>
<td>Med.</td>
<td>High</td>
<td>Base</td>
<td>767.0</td>
<td>35880</td>
</tr>
<tr>
<td>7</td>
<td>Base</td>
<td>Comb.</td>
<td>Low</td>
<td>Base</td>
<td>786.5</td>
<td>36650</td>
</tr>
<tr>
<td>8</td>
<td>Base</td>
<td>Comb.</td>
<td>Base</td>
<td>Base</td>
<td>795.5</td>
<td>37070</td>
</tr>
<tr>
<td>9</td>
<td>Base</td>
<td>Comb.</td>
<td>High</td>
<td>Base</td>
<td>800.0</td>
<td>37280</td>
</tr>
<tr>
<td>10</td>
<td>Base</td>
<td>Base</td>
<td>Low</td>
<td>Fast</td>
<td>804.4</td>
<td>37480</td>
</tr>
<tr>
<td>11</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>Fast</td>
<td>812.7</td>
<td>37870</td>
</tr>
<tr>
<td>12</td>
<td>Base</td>
<td>Base</td>
<td>High</td>
<td>Fast</td>
<td>817.8</td>
<td>38110</td>
</tr>
<tr>
<td>13</td>
<td>Base</td>
<td>Comb.</td>
<td>Low</td>
<td>Fast</td>
<td>790.1</td>
<td>36820</td>
</tr>
<tr>
<td>14</td>
<td>Base</td>
<td>Comb.</td>
<td>Base</td>
<td>Fast</td>
<td>798.5</td>
<td>37210</td>
</tr>
<tr>
<td>15</td>
<td>Base</td>
<td>Comb.</td>
<td>High</td>
<td>Fast</td>
<td>802.8</td>
<td>37410</td>
</tr>
<tr>
<td>16</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>Slow</td>
<td>789.3</td>
<td>36780</td>
</tr>
<tr>
<td>17</td>
<td>Early</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>823.4</td>
<td>38370</td>
</tr>
<tr>
<td>18</td>
<td>Late</td>
<td>Base</td>
<td>Base</td>
<td>Base</td>
<td>772.1</td>
<td>35980</td>
</tr>
</tbody>
</table>

^Average over 18 years of simulated results.

^bBase run."
18 different CORNSIM runs. The average income column is an estimate of the cash value of the crop at harvest time, assuming delivery to an elevator for $116.50 per metric ton of dry matter ($2.50 per bushel at 15.5% MCWB) minus a drying charge of 1.75 cents per point of moisture above 15.5 percent per 25.4 kg wet weight (wet bushel). The average income is useful in comparing the alternate management strategies. A quick observation shows:

1. Hybrid selection and planting strategy are the key parameters to increase yield and income.
2. The increased yields due to beginning harvest at a higher moisture content approximately cover the increase in drying cost.
3. As the capacity of the harvest system increases the optimum beginning moisture content decreases.

(Note CORNSIM does not account for the value of additional fall field days available for tillage after harvest is completed.)

Bin Filling Strategy

Next, it is necessary to select a bin filling strategy to move the daily harvested grain flow data provided by CORNSIM into the drying system simulated by FALDRY. Three layer-filling methods were tested using the output of the "base" CORNSIM run (Run No. 2). They were as follows:

Method 1 - Series filling of four bins - layer fill each bin until full and then proceed to the next bin.

Method 2 - Parallel filling of four bins - layer fill all four bins simultaneously by adding one full day’s harvest to a bin and then
rotate to the next bin for the following day's harvest.

Method 3 - Layer fill one large bin.

The CORNSIM simulations are based on midsized Iowa farms with 121.4 hectares (300 acres) of corn. The four-bin drying system used bins 9.1 meters (30 feet) in diameter, accommodated up to 5.3 meters (17.5 feet) of grain, and each used an 8.8-kW fan. The one-bin system was exactly four times the storage capacity of the smaller bins, the same height, and used four 8.8-kW fans.

With Method 1, each bin was typically filled in 4 to 6 days based on CORNSIM output. With Method 2, all the bins were simultaneously filled over a 20- to 25-day period. Due to the longer filling time, Method 2 was expected to be much preferred. The third method was tested with the idea it could be used as an approximation of Method 2. Using Method 3 would save 75 percent on computer simulation cost. Table 7 shows the results of the test. By comparison with Method 1, the results showed Method 2 with an 8 percent energy saving, less grain deterioration as measured by dry matter loss, and, most importantly, a smaller number of failures. For practical purposes, there is no difference between Methods 2 and 3.

Effect of Varying CORNSIM Strategies

From the 18 CORNSIM runs (Table 6), the daily harvested grain flow data were used as input by FALDRY to test the feasibility of matching the capacities of the drying and harvesting systems. The grain was layer-filled into one large bin with an 18.3-meter (60-feet) diameter, 6.4-meter
Table 7. FALDRY results\(^a\) for three filling methods

<table>
<thead>
<tr>
<th>Filling method No.</th>
<th>Binning method</th>
<th>Drying time (hours)</th>
<th>Number of failures</th>
<th>Number of spring finishes</th>
<th>Average dry matter loss</th>
<th>Total drying energy kWh/metric ton kWh/bu</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (4 bins filled in series)</td>
<td>1</td>
<td>1189</td>
<td>8</td>
<td>8</td>
<td>.45%</td>
<td>51.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1060</td>
<td>2</td>
<td>8</td>
<td>.22%</td>
<td>46.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>997</td>
<td>1</td>
<td>9</td>
<td>.16%</td>
<td>43.3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>748</td>
<td>1</td>
<td>7</td>
<td>.13%</td>
<td>34.5</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>999</td>
<td>8</td>
<td>8</td>
<td>.24%</td>
<td>43.9</td>
</tr>
<tr>
<td>2 (4 bins filled in parallel)</td>
<td>1</td>
<td>1036</td>
<td>1</td>
<td>5</td>
<td>.15%</td>
<td>45.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>943</td>
<td>0</td>
<td>5</td>
<td>.12%</td>
<td>40.9</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>929</td>
<td>0</td>
<td>5</td>
<td>.10%</td>
<td>40.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>843</td>
<td>0</td>
<td>5</td>
<td>.09%</td>
<td>36.6</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>937</td>
<td>5</td>
<td>5</td>
<td>.11%</td>
<td>40.6</td>
</tr>
<tr>
<td>3 (1 large bin)</td>
<td>915</td>
<td>0</td>
<td>5</td>
<td>5</td>
<td>.09%</td>
<td>39.6</td>
</tr>
</tbody>
</table>

\(^a\) Average over 18 years of simulated results.

\(^b\) Dry matter loss exceeds .5%.

\(^c\) Average of the yearly maximums.
(21-feet) maximum grain depth, and a 35.1 kW of fan power\(^1\) (four 10-horsepower fans). Bin filling occurred daily except when harvest was curtailed by inclement weather or field trafficability. Table 8 summarizes the results. A careful study of the 324 bin-years of simulation yields several interesting observations:

1. The fall of 1972 was exceptionally cool and wet. The corn moisture was unusually high and bumper yields were harvested. This provides a severe test of a natural air-drying system. The single failures for Runs 1, 7, 10, and 13 as well as one of the failures for Runs 12 and 15 occurred in the spring following the 1972 harvest.

2. The combination of beginning harvest at 26% MCWB and fast harvest resulted in five fall drying season failures, one for Run 12, and four for Run 15.

3. The "Comb." hybrid selection strategy was effective in increasing the number of fall finishes when grain harvest began at 24% MCWB and 26% MCWB moisture; but when included with "Fast" harvest and "High" harvest moisture in Run 15, the "Comb." hybrid selection resulted in six failures.

4. Each 2 percent decrease in beginning harvest moisture results in a significant decrease in total drying time; but in many cases this reduction in drying time was approximately equal to the

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\(^1\)Note - Appendix A reports on the effects of varying fan power and heater size for the layer-filled drying of CORNSIM Runs 1, 2, and 3. These results were the basis for selecting 35.1 kW of fan power with no heater.
### Table 8. FALDRY results\(^a\) for the 18 CORNSIM runs

<table>
<thead>
<tr>
<th>CORNSIM Run No.</th>
<th>Average harvest MCWB%</th>
<th>Drying time hours</th>
<th>Number(^b) of failures</th>
<th>Number of spring finishes</th>
<th>Average dry(^c) matter loss (%)</th>
<th>Total drying energy kWh/t kWh/bu</th>
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</thead>
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</table>

\(^a\) Average over 18 years of simulated results.

\(^b\) Dry matter loss exceeds .5%.

\(^c\) Average of the 18 yearly maximums.
time required for the grain to dry in the field to the next harvest moisture.

5. Each 4-hour-per-day increase in "Harvest Capacity" (1200 bushels per day increase) roughly doubles the average maximum dry matter loss.

6. The changes in "Planting" strategy had no significant effect on the overall performance of the drying system.

7. No failure occurred with a beginning harvest moisture content of 24 percent.

Conclusions

Based on the simulation results from CORNSIM and FALDRY, the following conclusions are given for Central Iowa conditions. It is expected the findings would be similar for most of the Corn Belt.

1. Planting strategy and hybrid selection are the key management variables to maximize production.

2. Harvest rate and beginning harvest moisture are the key management variables that affect the success of natural air grain drying and the energy requirements.

3. The optimum grain moisture content to begin harvest is 24 percent MCWB. For harvesting systems with low capacity, the optimum increases to 26 percent MCWB, whereas a high capacity harvesting system could begin at 22 percent MCWB.

Note - The hybrid selection defaults in the "Base Management Strategy" does not allow extra late planting of any corn. Thus, the problem of harvesting and drying exceptionally wet and immature grain has not been studied.
4. For a natural air system, the drying energy per unit of grain per point of moisture removal decreases as the initial grain moisture increases because:

a. Higher initial moisture content is associated with early harvest when the ambient air has a higher moisture absorbing capacity.

b. The ventilation air exits the grain nearer to saturated conditions.

5. Natural air drying systems with fan power to grain ratios commonly in use are feasible for midsize Iowa farms if the daily harvest rate is about 1/16 of the total production.
DEVELOPMENT OF AN OPTIMUM CONTROLLED FILLING STRATEGY

Introduction

While studying the feasibility of matching a layer-filled, natural air system with harvest capacity of a typical, midsize farm, it became apparent that farmers would need a simple daily filling strategy to guide their harvesting schedule. The parameters developed in the previous section are essential in design of a balanced system. But as farm size, harvesting capacity, management strategies, etc., change, the farmer needs an optimum controlled filling strategy that lets him harvest as fast as possible dependent on the weather and field conditions and without unacceptable deterioration of his grain. The strategy must meet the following objectives:

1. Maintain grain quality.
2. Begin harvesting as soon as possible.
3. Maximize the overall filling rate.
4. Allow harvest to proceed at a reasonably uniform rate.
5. Minimize the drying energy required.
6. Be easily understood by farm managers.
7. Require a minimum of time so as to not interfere with harvest.
8. Use information and instruments readily available.
Safe Airflow

The basic assumption behind the development of controlled filling is that the transient ratio of airflow per unit of wet grain is the determining factor for successful drying. Thus, it becomes necessary to develop a relationship between incoming grain moisture and the minimum safe airflow. The information available in the literature is not valid for this application. The available information was developed assuming all the grain in the bin had a uniform moisture content, whereas in a controlled-filled bin the initial moisture content of each layer will vary, usually being successively drier.

A trial and error procedure using a modified drying model was developed. Each of 10 layers in the bin was filled with the highest moisture content possible without exceeding 0.5% dry matter deterioration. These tests were run using 1968 weather data assuming the bin was filled on October 15 with a 1.4°C (2.5°F) heat rise and 0.013 m³/s·m³ (1 cfm/bu) average airflow. After computing the effective airflow for each layer, the values in Table 9 were determined to be the first approximation of a minimum safe airflow. As expected, the numbers are significantly higher than previously published values because the grain in each of the layers below the object layer is at successively higher moisture contents. Predicting the minimum safe airflow is a probability game because one is being asked to predict the worst possible weather conditions from the filling date until the drying front passes through the grain in the layer being filled.
Table 9. Minimum safe airflows

<table>
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<th>Grain moisture</th>
<th>Airflow</th>
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<td>% MCWB</td>
<td>m /s·m³</td>
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<td>0.013</td>
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<tr>
<td>20</td>
<td>0.027</td>
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<tr>
<td>22</td>
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<td>0.080</td>
</tr>
<tr>
<td>27</td>
<td>0.121</td>
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</table>

Development of a Simulation Model and Testing

Modified versions of CORNSIM and FALDRY were used to develop and test several controlled-filling strategies. First CORNSIM was used to create profiles of harvested grain moisture versus calendar date for each of the 18 harvest seasons to be tested. Table 10 outlines the CORNSIM management strategy to produce three sets of harvest moisture profiles.

Table 10. CORNSIM management strategy

<table>
<thead>
<tr>
<th>Crop maturity</th>
<th>Planting strategy</th>
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<tbody>
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<td>Early</td>
<td>Medium season corn planted on April 26</td>
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<tr>
<td>Average</td>
<td>Full season corn planted on April 26</td>
</tr>
<tr>
<td>Late</td>
<td>Full season corn planted on May 10</td>
</tr>
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</table>

A monitoring and management subroutine OPTDRY was added to FALDRY to simulate the trial controlled-filling strategies. OPTDRY simulates a 20-layer bin and daily monitors the location of the initial drying front.
by checking for the position of grain moistures above and below 17.5% MCWB. Based on the position of the initial drying front, the transient ratio of airflow per unit of wet grain, calendar date, availability of harvested grain, and/or grain moisture in the field, OPTDRY determines the amount, if any, of grain that can be layer-filled into the bin each day.

Several controlled-filling strategies were tested against the three sets of harvest moisture profiles with a complete range of practical fan-power-to-grain ratios. The first test strategy divided the harvest season into three periods. Separate minimum safe airflow versus grain moisture relationships were developed for each period. This strategy had several weaknesses:

1. It was too complex to be easily implemented.
2. For high fan-power-to-grain ratios it resulted in very uneven filling. Typically it began with one large filling of very wet grain and then tailed off rapidly.
3. It resulted in very conservative airflow versus grain moisture relationships especially for the early harvest period.
4. It failed to account for the moisture absorbing benefit of the dry grain in the bin as a hedge against unfavorable weather in the future.

Further efforts centered around simplifying the controlled-filling procedure and developing maximum daily filling depths based on grain harvest moisture and the location of the drying front in the bin.

The optimum controlled-filling strategy is outlined in Figure 8.
OPTIMUM CONTROLLED FILLING STRATEGY

- BEGIN FILLING AS SOON AS THE HARVESTED GRAIN MOISTURE IS 26% MCWB OR LESS

- THE MAXIMUM DAILY FILLING DEPTH IS 1.2 METERS (4 FEET) UNLESS HARVESTED GRAIN MOISTURE EXCEEDS 24% MCWB. THEN THE MAXIMUM FILLING DEPTH IS 0.6 METERS (2 FEET).

- IF HARVESTED GRAIN MOISTURE EXCEEDS 22% MCWB, THE INITIAL DRYING FRONT MUST BE AT LEAST HALFWAY UP THE GRAIN PROFILE BEFORE ADDITIONAL FILLING IS ALLOWED.

- THE MINIMUM SAFE AIRFLOW FOR THE INCOMING GRAIN MOISTURE (CHART BELOW) MUST BE MET.

\[
\text{m}^3/\text{s} \cdot \text{m}^3 \quad (\text{cfm/bu})
\]

- LAYER FILLING MAY BE SKIPPED ON ANY DAY IF THE QUANTITY TO BE ADDED IS TOO SMALL TO MAKE FILLING PRACTICAL OR OTHER HARVEST ACTIVITIES TAKE PRECEDENCE.

Figure 8. Optimum controlled-filling strategy
The maximum daily fill depth of 1.2 meter (4 feet), with a 0.6 meter (2 feet) fill depth above 24% MCWB, tended to level out the harvest rate over the filling period and reduce the drying energy by reducing the quantity of wet grain added during the early stages of layer filling. The limitation had virtually no effect on the overall filling time. The limit of 0.6 meter (2 feet) filling depth for harvested grain over 24% MCWB and the requirement for drying front progress before adding grain over 22% MCWB, eliminated the need for two or three sets of minimum safe airflows dependent on filling date. These controlled-filling rules were also effective in eliminating spoilage problems on some critical combinations of grain, weather, and bin specifications.

The optimum controlled-filling strategy is a generalized strategy applicable over a wide range of fan-power-to-grain ratios and bin dimensions. Assuming 1 kilowatt fan power per 21.5 tons (1,000 bushels) of grain with typical fall weather conditions, the strategy would result in a planned filling schedule of 1/16 the bin depth each day, 1/8 every other day, or 1/4 every fourth day. Filling would be completed in a little over 2 weeks, and drying would be finished in about 6 weeks.

Table 11 gives a year-by-year summary of the drying performance of a 9.1 meter (30 feet) diameter, 5.3 meter (17.5 feet) deep bin powered by 8.8 or 13.2 kilowatts of fan power. The results were based on drying grain from the CORNSIM "average" harvest moisture profile. The year-to-year variations in moisture profiles and dryer performance are significant.

Figure 9 graphically illustrates the effects of varying electrical
Table 11. Controlled-filling drying performance using CORNSIM
"average" harvest moisture profile

<table>
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<tr>
<th>Year</th>
<th>Fan size (kW)</th>
<th>Filling operation</th>
<th>No. days Drying complete</th>
<th>Drying time</th>
<th>Drying energy (kWh/t)</th>
<th>Dry matter loss (kWh/bu)</th>
<th>Average</th>
<th>Maximum</th>
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<td>10/15 9 11/2 648</td>
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*Spring finish required.*
Figure 9. Controlled-filling drying performance
fan power for a 9.1 meter (30 feet) diameter by 5.3 meter (17.5 feet) deep bin using the average harvest moisture profile. As the electrical fan power increases, the drying time decreases, the drying energy increases, and dry matter loss is reasonably constant. This confirms that the optimum controlled-filling strategy is effectively regulating the filling schedule so as to maximize the filling rate while maintaining acceptable grain quality.

Table 12 gives drying results using the optimum controlled-filling strategy for a range of fan-power-to-grain ratios for three CORNSIM harvest moisture profiles. These results indicate that the objectives for a controlled-filling strategy, outlined in the Introduction of this section, have been met. Appendix B illustrates how the optimum controlled-filling strategy can be implemented by a farm manager.

Conclusions

Based on the simulation results, the following conclusions are given for Central Iowa conditions. It is expected the results would be similar for most of the Corn Belt.

1. The optimum controlled-filling strategy is recommended for bins with a grain depth of 5 to 6 meters and a fan-power-to-grain ratio of 1 to 1.5 kilowatts per 21.5 tons (1,000 bushels) of bin storage capacity.

2. Using controlled filling, the bins can typically be filled in 2 to 3 weeks and successfully dried with about 1,000 hours of fan operation. Assuming a farmer has natural air drying bins for
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<th>Average^d</th>
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^a Average for 18 years of simulated results for a 9.14 m (30 feet) diameter by 5.33 m (17.5 feet) grain depth bin.

^b None of the 216 bin simulated exceeded .5% dry matter loss in any layer.

^c Includes non-harvest days due to unsuitable field trafficability.

^d Average of 18 yearly maximums.
his entire crop, he can expect to harvest 5 to 8% of his total production every day, weather permitting, without exceeding the system capacity.

3. Operating with the recommended fan-power-to-grain ratio, the drying energy requirements average 51 kWh/t (1.1 kWh/bu) with ideal years near 50 percent of the average and problem years twice the average amount.

4. With the controlled-filling strategy, harvest can begin with a corn moisture of 26% MCWB. A 2 percent moisture reduction in beginning moisture content may result in about 10 percent energy savings. Waiting for field moisture to drop below 24% MCWB is not recommended.

5. The optimum controlled-filling strategy enables the farm manager to:
   a) Fill drying bins as rapidly as possible to suit the current harvest and drying conditions.
   b) Assure successful drying every year, utilizing drying in the spring following difficult seasons.
   c) Complete drying without unacceptable deterioration.
SUGGESTIONS FOR FURTHER RESEARCH

The process of developing and using computer simulation models can make the researcher painfully aware of voids in the reported research and limitations of the simulation process. The following tasks are suggested for future study and development.

1. Develop a winter aeration strategy that minimizes fan energy and maintains grain quality for low-temperature drying bins when drying was not completed in the fall.

2. Determine the effect of quantity and distribution of broken corn and foreign material on uniformity of airflow in the bin.

3. Determine the effect of grain distribution and layer filling on uniformity of airflow in the bin.

4. Conduct field test of the optimum controlled-filling strategy.

5. Observation of farmers using the controlled-filling strategy to determine the level of understanding and management skill required.

6. Conduct an economic analysis of controlled filling.

7. Simulation of corn and soybean harvesting using the controlled-filling strategy.
REFERENCES


APPENDIX A:

EFFECTS OF VARYING FAN AND HEATER SIZES
FOR A LAYER-FILLED BIN

Tables A.1, A.2, and A.3 summarize the results of 900 bin-years of simulated drying experiments. The daily harvested grain flow data provided by CORNSIM Runs 1, 2, and 3 were layer-filled into an 18.3 meter (60 feet) diameter by 6.4 meter (21 feet) high steel bin with the fan and heater sizes as tabulated. The tabulated results are the average values over 18 years of simulated tests. The results are conclusive: Electrical energy is most effectively used when it powers a "fan power only" system.
Table A.1. Layer-filling CORNSIM Run No. 1 (base conditions with 22% MCWB harvest)

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Table A.2. Layer-filling CORNSIM Run No. 2 (base conditions with 24% MCWB harvest)

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<td>-</td>
<td>87.7</td>
<td>625</td>
<td>12.7</td>
<td>62.1</td>
<td>1.45</td>
<td>.201</td>
<td>.13</td>
</tr>
</tbody>
</table>

*Only accounting for moisture removed above 15% MCWB.*
Planning a controlled-filling strategy for a specific low-temperature corn drying system can be accomplished using

1. Bin capacity chart (Table B.1)
2. Average airflow chart (Table B.2)
3. Maximum wet grain depth (Table B.3)

The controlled-filling strategy is implemented during corn harvest and fall drying using

1. Rules for fan management (Figure B.1)
2. Rules for controlled-filling (Figure B.2)
3. Maximum wet grain depth (Table B.3)

Winter aeration and spring drying, if necessary, are accomplished using

1. Rules for fan management (Figure B.1)

---

1 The purpose of this section is to illustrate how a Central Iowa farmer would use the optimum controlled-filling strategy; therefore, all quantities will be in English units.
PLANNING FOR CONTROLLED FILLING

PREPARE PLAN

1. Using Table B.1, determine the quantity of grain per foot of bin depth.

2. Using Table B.2, determine the system performance for the drying fan and the drying bin. From fan performance curves or charts (furnished by fan manufacturer or dealer), determine the fan discharge at 3 inches of water. Determine the average airflow.

3. Using Table B.3, highlight the system performance at 3 inches of water. This approximates system performance for the intermediate stage of bin filling, 6 to 12 feet of grain depth.

4. Using Table B.3, highlight the system performance for the beginning and final stages of bin filling. The next higher airflow rate will approximate the beginning stage of filling, 0 to 6 feet of grain depth. The next lower airflow rate will approximate the final stage of filling, 12 to 18 feet of grain depth.

5. Another step prior to harvest will prove helpful. Paint a grain depth scale on the inside bin wall.

EXAMPLE

1. 30 ft dia bin, 17.5 ft grain depth, 10,000 bu. capacity. Find 570 bu. per foot of depth.

2. 10 hp fan, 12,000 cfm @ 3 inches of H₂O

3. Underline the wet grain depths for the average flow of 16 cfm/ft² and label as Intermediate 6 - 12 ft.

4. Underline the next higher airflow @ 18 cfm/ft², and label, Beginning 0 - 6 ft. Underline the next lower airflow @ 14 cfm/ft² and label, Final 12 - 18 ft.

5. Paint grain depth scale in one-foot increments in 2 or 3 equally-spaced intervals around the bin.

1 Based on a fan-power-to-grain-ratio of 1.25 to 1.75 Hp per 1,000 bushels of corn and a corn depth of 16 to 20 feet.

2 Assumes use of an axial-flow fan.
Table B.1. Bin capacity chart

<table>
<thead>
<tr>
<th>Bin diameter (feet)</th>
<th>Quantity of corn (bushels/foot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>200</td>
</tr>
<tr>
<td>21</td>
<td>280</td>
</tr>
<tr>
<td>24</td>
<td>360</td>
</tr>
<tr>
<td>27</td>
<td>460</td>
</tr>
<tr>
<td>30&lt;sup&gt;a&lt;/sup&gt;</td>
<td>570&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>33</td>
<td>690</td>
</tr>
<tr>
<td>36</td>
<td>820</td>
</tr>
<tr>
<td>42</td>
<td>1110</td>
</tr>
<tr>
<td>48</td>
<td>1450</td>
</tr>
</tbody>
</table>

<sup>a</sup>Sample problem solution.
Table B.2. Average airflow (cfm/ft\(^2\)) for different bin diameters and fan discharges

<table>
<thead>
<tr>
<th>Fan Discharge (cfm)</th>
<th>Bin Diameter (Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>18</td>
</tr>
<tr>
<td>1,000</td>
<td>3.9</td>
</tr>
<tr>
<td>2,000</td>
<td>7.8</td>
</tr>
<tr>
<td>3,000</td>
<td>11.8</td>
</tr>
<tr>
<td>4,000</td>
<td>15.7</td>
</tr>
<tr>
<td>5,000</td>
<td>19.6</td>
</tr>
<tr>
<td>6,000</td>
<td>23.6</td>
</tr>
<tr>
<td>7,000</td>
<td>27.6</td>
</tr>
<tr>
<td>8,000</td>
<td>31.4</td>
</tr>
<tr>
<td>9,000</td>
<td>35.3</td>
</tr>
<tr>
<td>10,000</td>
<td>39.0</td>
</tr>
<tr>
<td>12,000</td>
<td>43.6</td>
</tr>
<tr>
<td>14,000</td>
<td>48.4</td>
</tr>
<tr>
<td>16,000</td>
<td>53.2</td>
</tr>
<tr>
<td>18,000</td>
<td>58.0</td>
</tr>
<tr>
<td>20,000</td>
<td>62.8</td>
</tr>
<tr>
<td>22,000</td>
<td>67.6</td>
</tr>
<tr>
<td>24,000</td>
<td>72.4</td>
</tr>
<tr>
<td>26,000</td>
<td>77.2</td>
</tr>
<tr>
<td>28,000</td>
<td>82.0</td>
</tr>
<tr>
<td>30,000</td>
<td>86.8</td>
</tr>
<tr>
<td>34,000</td>
<td>92.4</td>
</tr>
<tr>
<td>36,000</td>
<td>97.0</td>
</tr>
<tr>
<td>42,000</td>
<td>105.0</td>
</tr>
<tr>
<td>46,000</td>
<td>110.0</td>
</tr>
<tr>
<td>50,000</td>
<td>115.0</td>
</tr>
<tr>
<td>54,000</td>
<td>120.0</td>
</tr>
</tbody>
</table>

\(^a\) Sample problem solution.
Table B.3. Maximum wet grain depth above the drying front

<table>
<thead>
<tr>
<th>Average Airflow (cfm/ft(^2))</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>15</td>
<td>7.5</td>
<td>5.0</td>
<td>3.7</td>
<td>3.0</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>6.6</td>
<td>5.0</td>
<td>4.0</td>
<td>3.3</td>
<td>2.5</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>8.3</td>
<td>6.2</td>
<td>5.0</td>
<td>4.1</td>
<td>3.1</td>
<td>2.5</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>15</td>
<td>10</td>
<td>7.5</td>
<td>6.0</td>
<td>5.0</td>
<td>3.7</td>
<td>3.0</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>14 Final(^a) (12 -18 ft)</td>
<td>18</td>
<td>11</td>
<td>8.7</td>
<td>7.0</td>
<td>5.8</td>
<td>4.4</td>
<td>3.5</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>16 Intermediate(^a) (6 -12 ft)</td>
<td>13</td>
<td>10</td>
<td>8.0</td>
<td>6.6</td>
<td>5.0</td>
<td>4.0</td>
<td>3.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 Beginning(^a) (0-6 ft)</td>
<td>15</td>
<td>11</td>
<td>9.0</td>
<td>7.5</td>
<td>5.6</td>
<td>4.5</td>
<td>3.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>17</td>
<td>13</td>
<td>10</td>
<td>8.3</td>
<td>6.2</td>
<td>5.0</td>
<td>4.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>7.5</td>
<td>6.0</td>
<td>5.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>17</td>
<td>14</td>
<td>11</td>
<td>8.7</td>
<td>7.0</td>
<td>5.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Sample problem solution.
Rules for Fan Management

A. Fall Drying

Turn on the fan(s) as soon as you covered the floor of the bin with grain. Regardless of weather conditions, do not turn off the fan(s) until one of the following occurs:

1. Completing Drying
   All the grain on top surface of the bin is dried to 15.5% MCWB or less.

2. Fall Shutdown
   a. Calendar date after November 15, corn in the top of the bin is less than 30°F and less than 18% MCWB.
   b. Calendar date after December 1, corn in the top of the bin is less than 25°F and less than 20% MCWB.
   c. The date is December 15.

B. Winter Aeration

1. For normal fall shutdown
   The aeration should be accomplished during the daylight hours on clear, dry days (low relative humidity). The frequency rate of aeration depends on the grain moisture content in top of the bin. If grain moisture in the top of the bin is:
   a. Below 15.5% MCWB - operate the fan approximately 8 hours every other week.
   b. Between 15.5 and 18% MCWB - operate the fan approximately 8 hours every week.
   c. Between 18 and 20% MCWB - operate the fan approximately 16 hours every week.

2. Operation with grain moistures exceeding 20% MCWB. If the calendar date is after December 15, and the grain moisture in the top of the bin is above 20% MCWB, the fan should be controlled by a time clock to run during daylight hours.

C. Spring Drying

If drying is not completed in the fall, it is necessary to resume continuous fan operation as soon as the winter weather cycle breaks; typically sometime during the month of March. Once again, having started drying, the fan runs continuously until completion of drying.

^Immediately upon completion of fall drying, begin winter aeration.

Figure B.1. Rules for fan management
Table B.4. Example of controlled filling

<table>
<thead>
<tr>
<th>Calendar date</th>
<th>Grain moisture in the field</th>
<th>Bin condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% MO/B</td>
<td>Total grain (bu)</td>
</tr>
<tr>
<td>Month</td>
<td>Day</td>
<td></td>
</tr>
<tr>
<td>Oct.</td>
<td>10</td>
<td>26.0</td>
</tr>
<tr>
<td>Oct.</td>
<td>11</td>
<td>25.5</td>
</tr>
<tr>
<td>Oct.</td>
<td>12</td>
<td>25.0</td>
</tr>
<tr>
<td>Oct.</td>
<td>13</td>
<td>24.5</td>
</tr>
<tr>
<td>Oct.</td>
<td>14</td>
<td>23.5</td>
</tr>
<tr>
<td>Oct.</td>
<td>15</td>
<td>23.0</td>
</tr>
<tr>
<td>Oct.</td>
<td>16</td>
<td>22.5</td>
</tr>
<tr>
<td>Oct.</td>
<td>17</td>
<td>22.0</td>
</tr>
<tr>
<td>Oct.</td>
<td>18</td>
<td>21.5</td>
</tr>
<tr>
<td>Oct.</td>
<td>19</td>
<td>21.0</td>
</tr>
<tr>
<td>Oct.</td>
<td>20</td>
<td>20.5</td>
</tr>
<tr>
<td>Oct.</td>
<td>21</td>
<td>20.25</td>
</tr>
<tr>
<td>Oct.</td>
<td>22</td>
<td>20.0</td>
</tr>
<tr>
<td>Oct.</td>
<td>23</td>
<td>-</td>
</tr>
<tr>
<td>Oct.</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>Oct.</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>Oct.</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>Nov.</td>
<td>11</td>
<td>-</td>
</tr>
</tbody>
</table>

Drying complete

a As determined from Table B3.
b Includes limitations for controlled filling, Figure B2.
c Calculated using Table B1.
d Chose to disregard increments less than 1.5 feet.
Filling completed.
Rules for Controlled Filling

1. Begin harvest as soon as the corn moisture in the field is 26% MCWB or less.

2. For corn 24% to 26% MCWB, the maximum daily filling depth is 2 feet.

3. For corn below 24% MCWB, the maximum daily filling depth is 4 feet.

4. For corn 22% MCWB and above, the initial drying front must be at least halfway up the grain profile before additional filling is allowed.

5. For all incoming corn moistures, the filling depth may not accumulate corn to exceed the maximum recommended wet grain depth, Table B.3.

6. Controlled filling may be skipped on any day the quantity allowed is too small to be practical or other harvest activities take precedence.

Figure B.2. Rules for controlled filling
CONTROLLED FILLING

1. Figure B.1 gives the guidelines for drying fan management including fan start-up, completion of drying, fall shutdown, and spring drying, if necessary.

2. Figure B.2 gives the rules for controlled filling.

3. Table B.3, as prepared for the specific drying system, provides the information for applying Controlled Filling Rule 5.

4. The requirements of Controlled Filling Rules 4 and 5 must both be met before additional grain filling is allowed.

5. During the early stages of filling, Rules 2, 3, and 4 usually control. During intermediate stages of filling, Rules 4 and 5 usually control. For the latter stages of filling, Rule 5 usually controls.

EXAMPLE OF CONTROLLED FILLING

Table B.4 illustrates a control filling process using the example problem. The application of the rules for controlled filling, Figure B.2, and the maximum wet grain depth, Table B.3, is illustrated on a daily basis. For the purpose of illustration, simplifying assumptions were made concerning grain drydown in the field and advancement of the drying front in the bin.
SUMMARY OF CONCLUSIONS

1. CORNSIM is a valid simulation model of corn production systems for Central Iowa. It can be used to determine the relative effects of changes in production strategy.

2. FALDRY is a valid simulation model of a low-temperature corn drying system. It has the flexibility to accommodate layer-filling and is able to predict the grain moisture profile.

3. The following design criteria and management strategy are recommended for low-temperature corn drying systems located in Central Iowa:
   a) Maximum grain depth of 16-20 feet.
   b) Fan-power-to-grain ratio of 1.25 to 1.75 horsepower per 1000 bushels of bin storage capacity.
   c) Use a high-performance axial fan (large bin may require 2 or more fans).
   d) Follow the controlled-filling strategy.
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