A digital electronic control system for low-temperature drying of shelled corn

Glenn Allen Kranzler
Iowa State University

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A digital electronic control system
for low-temperature drying of shelled corn

by

Glenn Allen Kranzler

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For the Graduate College

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LIST OF SYMBOLS AND DEFINITIONS

bit
Binary digit

bu
Bushel

c/day
Clock frequency (cycles/day)

c/hr
Clock frequency (cycles/hr)

cfm
Airflow rate (cubic ft/min)

cfm/bu
Airflow rate per unit volume (cubic ft/min-bu)

CLK
Clock

CLR
Clear

CMOS
Complementary metal-oxide semiconductor

DIS
Disable

EMC
Equilibrium moisture content (percent, w.b.)

enable
Logic signal permitting a control action to take place

F
Fahrenheit

ft
Feet

gate
Logic circuit having two or more inputs and one output

H
Electric heater capacity (kW)

hr
Hour

Hz
Hertz (cycles/sec)

IC
Integrated circuit

in
Inch

kW
Kilowatt

inhibit
Logic signal preventing an action from taking place

min
Minute

mW
Milliwatt
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<tr>
<td>nW</td>
<td>Nanowatt</td>
</tr>
<tr>
<td>PROM</td>
<td>Programmable read-only memory</td>
</tr>
<tr>
<td>Q</td>
<td>Airflow rate (cfm/bu)</td>
</tr>
<tr>
<td>R</td>
<td>Resistor</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity (percent)</td>
</tr>
<tr>
<td>$T_{\text{amb}}$</td>
<td>Dry-bulb temperature (degrees F)</td>
</tr>
<tr>
<td>$T_L$</td>
<td>Time for emergence of leading edge of temperature-transition zone (hr)</td>
</tr>
<tr>
<td>$T_r$</td>
<td>Heater temperature rise (degrees F)</td>
</tr>
<tr>
<td>TTL</td>
<td>Transistor-transistor logic</td>
</tr>
<tr>
<td>VAC</td>
<td>Volts, alternating current</td>
</tr>
<tr>
<td>$V_{cc}$</td>
<td>Logic supply voltage (volts, DC)</td>
</tr>
<tr>
<td>word</td>
<td>Group of bits of defined length</td>
</tr>
<tr>
<td>w.b.</td>
<td>Wet basis</td>
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INTRODUCTION

Low-temperature grain drying is similar in concept to drying with natural air. Incoming atmospheric air provides the primary energy source for removing the moisture. The grain is conditioned in storage at full-bin depth. With low-temperature drying, the air is heated electrically a few degrees above ambient to raise its drying capacity. Low fall air temperatures restrict spoilage arising from mold growth in the slowly drying product.

Interest in low-temperature drying has grown in recent years. The increasing expense and uncertainty of fuel supplies for conventional high-temperature dryers have been influential. Other factors favoring the low-temperature approach include simpler equipment requirements, more efficient use of energy inputs, and higher quality of the conditioned product. Of the more than 55,000 grain dryers used in Iowa in 1975, over 17 percent were electric low-temperature units (Iowa Crop and Livestock Reporting Service, 1976).

Because outside air dominates the low-temperature drying process, conditioning progress is slow and weather-dependent. Limits on safe storage time, governed largely by grain moisture content and temperature, impose restrictions on system operation. Under unfavorable drying conditions, skillful management is required to dry the grain before it spoils.

Although the low-temperature drying process is complex and subject to local weather variations, present management practices follow broad empirical recommendations. Past results indicate that manual operation based on general guidelines ensures neither optimum drying nor efficient use of
energy inputs. Controls to assist management, when present, are limited in scope and effect. A need exists for more comprehensive controls capable of increasing efficiency and reducing management requirements. Such controls are not currently available.

Controls for low-temperature drying have received little research attention. Previous control studies have concentrated on high-temperature systems. Emphasis has been on liner control techniques employing continuous analog signals. Subsequent developments in electronic digital logic suggest the desirability of the nonlinear (digital) approach. Digital control techniques are particularly compatible with the simple, on-off ambient sensors appropriate for use with low-temperature drying systems.
LITERATURE REVIEW

Low-Temperature Drying

Slow drying of cereal grains with unheated or natural air was practiced frequently before the adoption of high-speed, high-temperature methods. Foster (1953) studied the drying effects of unheated airflows ranging from 0.5 to 4 cubic feet per minute per bushel (cfm per bu). For moderate fall Indiana weather, 3 cfm per bu appeared to be adequate for drying shelled corn from 25 to 15.5 percent moisture content. The amount of grain deterioration or spoilage during drying was found to be closely related to the length of the drying period and the temperature of the drying air.

Hukill (1954) compared the effect of airflow direction on bulk drying of oats and corn with natural air and cited advantages of a pressure bin configuration over suction operation.

The natural-air drying process was subsequently investigated by Hukill and Shedd (1955). They concluded that a drying "zone" of limited depth progresses through the grain mass. Grain located downstream from the drying zone remains at the initial moisture content until reached by the advancing drying zone. The time required for drying was shown to be proportional to the ventilation rate.

In laboratory experiments on shelled corn, Saul and Lind (1958) investigated the period of time allowable for natural-air drying before the onset of spoilage due to active mold growth. The deterioration rate, as

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Grain moisture contents are expressed as a percentage of moisture based on wet weight (wet basis).
determined by dry matter decomposition, was reported to be from six to eight times greater for high initial grain moisture contents (25 to 28 percent) than for low moisture levels (19 and 22 percent).

The direct relationship between deterioration rate and the moisture content and temperature of the grain was further quantified by the U.S. Department of Agriculture (1968) and Steele et al. (1969). A table and equations were presented for determining safe storage periods during which shelled corn would undergo up to a 0.5 percent dry matter loss but still retain its market grade.

These guidelines for allowable safe storage time found extensive application in the design and modeling of natural-air and low-temperature drying systems. The criteria were later updated by Saul (1970). He reported the deterioration rate of moist shelled corn at low temperatures to be approximately half of that described earlier.

McCune et al. (1963) and Shove (1968, 1969) exploited the favorable low-temperature storage life by using mechanically chilled air to rapidly cool and slowly dry grain in bulk storage. The relatively high electrical energy inputs reported were attributed largely to the air-conditioning load (Shove, 1970b).

Shove (1970a, 1971) combined and extended aspects of the refrigerated-air and natural-air drying concepts. He noted that in much of the Corn Belt low average daily air temperatures during harvest favor extended storage life and permit limited drying. However, because of the high concurrent relative humidity, natural air can seldom dry shelled corn to moisture levels low enough for safe storage. By increasing the air temperature only a few degrees, the relative humidity can usually be lowered sufficiently to
achieve a safe terminal moisture content without jeopardizing allowable storage time during drying. Electric resistance heat can provide the low levels of supplemental energy required.

Using this "low-temperature" drying concept, Shove (1971, 1972) conducted successful field drying experiments on shelled corn and developed basic design criteria for low-temperature drying systems. Low-temperature drying has subsequently become an accepted method of grain conditioning in the Midwest (Loewer et al., 1973; Arnholt and Rupp, 1974; Anderson, 1975; Farm Electrification Council, 1976).

Recently, low-temperature drying has received increased interest as a result of energy shortages and renewed research activity in solar grain drying (Bauman et al., 1975; Kranzler et al., 1975; Meyer et al., 1975; Morey and Nelson, 1975; Peterson and Hellickson, 1975). It has been shown that the low heat requirements and the ability to accommodate fluctuating input air temperatures make low-temperature drying directly compatible with solar supplementation.

Simulation of Low-Temperature Drying

The low-temperature drying process is exceedingly complex. It involves many continuously changing temperature and moisture profiles within both the conditioning air and the grain. Computer models designed to simulate the process reflect this inherent complexity.

Two general approaches to the simulation of low-temperature drying have been developed. The first, sometimes called the nonequilibrium model, is based on fundamental mechanisms of heat and mass transfer. Energy and mass balances defining conditions within the grain mass are described by a
set of partial differential equations. Solution requires the use of numerical techniques.

In the second approach, temperature and moisture equilibria between the air and the grain are assumed. The near-ambient temperatures and low airflow rates associated with low-temperature drying underlie this assumption. Theoretical and empirical equations requiring iterative solution describe air and moisture relationships within the grain mass in this "equilibrium model."

Nonequilibrium models

The first digital computer model of deep-bed grain drying to employ basic laws of heat and mass transfer was described by Boyce (1966). Boyce limited his simulation to the processes of heating and drying, isothermal drying, and direct heat transfer.

A similar, but somewhat less refined, procedure for computing moisture content in a deep bed of grain was proposed by Henderson and Henderson (1968). In a unique extension of the heat and mass transfer analysis, Hamdy and Barre (1970) used an analog-digital hybrid computer to simulate deep-bed grain drying.

Perhaps the most sophisticated of the nonequilibrium deep-bed grain drying models has been developed by Bakker-Arkema et al. (1974). This model simulates the deep-bed drying process with a set of four equations consisting of three partial differential equations derived from energy and mass balances and an empirical thin-layer drying equation. Because this approach is based on generalized heat and mass transfer analyses, it may be applied to predicting heating or cooling with drying or moisture adsorption.
for any biological product that satisfies the basic model assumptions. Although the model uses computer time conservatively, it is considered too slow for dynamic programming studies in which weather data are entered to simulate extended periods of drying (Bakker-Arkema et al., 1974).

Equilibrium models

Bloome and Shove (1971) described a low-temperature drying model based on the simplifying assumption that equilibrium is achieved between the air and the corn in each simulated grain layer. They showed that the model was capable of accurately predicting temperature and moisture content profiles in deep beds of shelled corn subjected to aeration in the ambient range. The model neglected heat loss through the bin wall and the heat of respiration.

Bloome and Shove (1972) later used this digital computer model to simulate the performance of low-temperature drying systems using 14 years of hourly weather data as input. Grain deterioration was determined from data presented by Steele et al. (1969). Cumulative probability curves were developed to predict successful drying as a function of airflow rate with up to 5°F of sensible heat added to the input air.

A mathematical model designed to simulate the performance of a temperature-controlled shelled corn storage system was developed and verified experimentally by Thompson et al. (1971). Changes in grain temperature and moisture content were predicted by dividing the storage bin into a series of stacked layers and applying an empirical thin-layer drying equation (Thompson et al., 1968) to each layer. The model considered respiration
and heat transfer through the bin walls and accepted prerecorded ambient air conditions as input.

Improvements in technique and procedure were included in a subsequent shelled-corn storage model (Thompson, 1972) that incorporated the equilibrium assumptions of Bloome and Shove (1971). Thompson (1972) used this model to simulate the effects of airflow rate, harvest date, initial moisture content, grain temperature, and weather conditions on storage deterioration. Results with 6 years of weather data from Lincoln, Nebraska, predicted that deterioration, as indicated by dry matter decomposition, is:

1. doubled for each 50 percent reduction in airflow, in the range of 0.5 to 2 cfm per bu,
2. halved for each 15-day delay in harvest, from October 1 to November 15,
3. doubled for each 2 percent increase in harvest moisture content, in the range of 20 to 25 percent,
4. is independent of grain temperature at harvest, and
5. may be doubled, as a result of seasonal differences in weather conditions.

Morey and Peart (1971) employed the Thompson model to determine least-cost systems for drying corn with natural air. A variation of the Thompson model was used by Flood et al. (1972) to establish design criteria for natural-air corn drying in southern Indiana. Finally, in a two-stage drying study involving partial high-temperature conditioning followed by low-temperature completion, Morey et al. (1976) estimated cooling and drying times with the Thompson model.
Controls for Grain Drying Systems

High-temperature systems

The use of controls for gas-fired, high-temperature grain drying systems is accepted practice (Brooker et al., 1974). The extent of control may vary. Some systems regulate only the drying-air temperature. On others, the entire drying process and all auxiliary grain-handling equipment are controlled automatically.

Matthews (1963) described an apparatus for automatically maintaining the desired moisture content from a continuous-flow drier. Control was achieved by varying the grain throughput rate in response to the signal from a capacitance-type moisture monitor. He later conducted field trials of the control system and found the regulation of moisture content to be generally satisfactory (Matthews, 1964).

Moisture-control systems for continuous-flow driers were investigated with the aid of a mathematical model by Zachariah and Isaacs (1966). Computer simulation was used to identify optimum controller constants and to predict system performance.

Aguilar and Boyce (1966) proposed the use of temperature ratios for the control of agricultural driers. They defined effective heat efficiency (E.H.E.) as the ratio of the sensible heat used in drying to the sensible heat in the drying air and related this ratio to grain moisture content, experimentally. An E.H.E.-sensing device was suggested to control drier flow rate or to halt drying at a predetermined E.H.E. value. The E.H.E. was reported to be an indicator of moisture content only under nonsaturated exhaust air conditions. As such, it is not a suitable control parameter for natural-air or low-temperature drying systems.
Agness and Isaacs (1967) evaluated exhaust air temperature as a measure of moisture content for the control of continuous-flow drying. Two control modes were studied using computer simulation and a laboratory prototype. With input parameters properly chosen, the performance of a simple two-position (on-off) system was found to equal that of proportional control. Under constant input-air temperature and airflow, the exhaust air temperature provided a satisfactory control indicator of grain moisture content. However, changes in initial moisture content of the grain required manual correction of the control system.

A regulator, based on the difference between the wet-bulb and dry-bulb temperatures, was investigated by Paine (1969) for peanut-drier control. Gas flow to the air heater was modulated in response to a differential temperature signal from the wet-bulb and dry-bulb sensors located in the heated airstream. The differential controller maintained drier operation within the recommended optimum drying zone with a minimum of management and operator skill.

Holtman and Zachariah (1969) demonstrated the feasibility of computer control for continuous-flow grain driers. A mathematical model of the drying process was incorporated in the control system to obtain adaptive or optimal control. Using simulated measurements of input and output moisture levels, the computer calculated the rate of flow required to maintain the desired moisture content. Such a system was proposed for large grain-handling facilities having telephone access to a time-sharing digital computer.
Low-temperature drying

Controls for natural-air and low-temperature drying systems have not received extensive research attention. Results of the reported control system studies have been mixed.

In an investigation of natural-air drying of wheat and shelled corn, Foster (1953) compared the effectiveness of continuous ventilation with that of intermittent ventilation under humidistatic control. The intermittent fan was operated only when the relative humidity of the air was below 85 percent. A combination of continuous ventilation for grain above 15.5 percent moisture content and intermittent ventilation for grain below that moisture level was judged to be the most effective method of fan operation.

Shove and Andrew (1969) field tested the performance of four different control methods for natural-air drying of shelled corn. The fan-control methods evaluated were: (1) continuous operation, (2) thermostat control, limiting operation to temperatures of 40°F and below, (3) photocell control, limiting operation to nighttime hours, and (4) manual control, at the discretion of the owner-operator. On the basis of final moisture content and grain condition, continuous aeration proved superior to the other control modes.

Flood et al. (1972) compared continuous and intermittent fan operation in a 10-season simulation study of natural-air corn drying. Results indicated that intermittent fan operation at moisture contents below 18 percent substantially reduced operating cost and produced less overdried grain.

Low-temperature drying with continuous ventilation and time clock-heater control was evaluated in a field study by Arnholt and Tuite (1976).
A mean daily relative humidity profile was developed from 5 years of local weather data for October and for November. Corresponding equilibrium moisture content values for shelled corn were plotted against hour of the day, noting the time interval during which low relative humidity dropped the equilibrium moisture content curve below the desired terminal moisture content. For each month, the time clock was programmed to turn off the heater during the hours showing a predicted equilibrium moisture content below the target level.

The resulting intermittent operation was compared with continuous operation on a second bin. On the basis of electrical energy required per bushel dried per percentage point of moisture removed, a 50 percent reduction in energy consumed was attributed to intermittent heater operation.

Arnholt and Tuite (1976) also field-tested manual control of the electric heater. The owner-operator switched off the heater whenever relative humidity readings indicated an equilibrium moisture content below the desired final moisture level. As compared with continuous heater operation, a 35 percent energy saving was reported.
OBJECTIVES

The overall objective of this investigation is to study the application of digital electronic controls to low-temperature drying of shelled corn to reduce spoilage risk, energy consumption, and management requirements. Specific objectives are twofold:

1. Development of an appropriate control scheme using computer simulation and long-term weather data.
2. Design of a digital electronic control system capable of implementing the required functions.
PROCEDURE AND RESULTS

The procedure and results of this investigation may be divided into two informally defined sections: (1) the development of a rational concept for the control of a low-temperature drying system and (2) the design of a practical control system capable of implementing the proposed control scheme.

Control development is based on a review of the low-temperature drying process and extensive computer simulation of drying using actual weather data as input. Simulation results are employed to predict control criteria for successful drying and to define appropriate control procedures and parameters. Performance of suggested control functions is evaluated by computer simulation over many seasons of operation.

The resulting control procedure is reduced to individual function modes which can be described in terms of static and sequential logic. Implementation assumes the use of standard input sensors and digital electronic components.

Low-Temperature Drying

Low-temperature grain drying may be classified as a fixed, deep-bed conditioning system (Brooker et al., 1974). Drying takes place in storage at full-bin depth. This method is designed for late-fall grain conditioning when low average daily air temperatures restrict mold growth in the slowly drying product. The grain is normally stored in the drying bin and held for spring sale.

Airflow rates employed are relatively low, ranging from 1 to 3 cfm per bu for shelled corn (Arnholt and Rupp, 1974). The air is heated
approximately 5°F to increase its drying potential and to permit drying the grain to a moisture content low enough for safe storage. Temperature rises exceeding 8°F are seldom used because of probable overdrying and the inverse relationship between temperature and safe storage time (Farm Electrification Council, 1976).

Low-temperature drying depends heavily on the energy in the ambient air for the heat of vaporization required to remove moisture from the grain. Because of the limited capacity of cool air to absorb moisture, drying progress is slow and weather-dependent. Normal drying times for shelled corn may extend from 30 to 50 days (Brooker et al., 1974). Unless storage over summer is anticipated, corn is considered to be safely "dry" when it reaches an average moisture content of about 15 percent (Shove, 1972). Grain that has not been fully dried before the onset of very cold weather can usually be kept in condition over winter and dried to completion in early spring (Shove, 1972; Arnholt and Rupp, 1974).

A typical low-temperature drying system is illustrated in Figure 1. The cylindrical metal drying/storage bin is equipped with a false floor of perforated metal to permit the passage of air. Ambient air, drawn into the system by a large, single-speed electric fan, is warmed by an electrical resistance heater. Motor and fan inefficiencies contribute an additional temperature rise of 2 to 3°F (Farm Electrification Council, 1976).

The heated air is forced into the plenum chamber and up through the wet grain column. Moisture is evaporated from the grain and carried out of the bin through roof vents. In order to facilitate uniform upward airflow, an electric-powered spreader is used to provide even distribution of the
Figure 1. Typical low-temperature drying system
grain during filling. Airflow is normally controlled by varying the depth to which the bin is filled.

Electric controls, if present, are usually minimal. Automatic cycling of the heater, by means of a humidistat, time clock, or differential thermostat, is sometimes included (Steffen, 1973; Farm Electrification Council, 1976).

Advantages cited for low-temperature drying include: (1) system equipment requirements are relatively simple (Farm Electrification Council, 1976), (2) filling flexibility permits the harvest to proceed at any desired rate (Brooker et al., 1974), (3) energy inputs are used more efficiently than with high-temperature drying (Hill and Shove, 1972), and (4) product quality is higher than with high-temperature methods (Shove, 1972).

Disadvantages include: (1) drying progress is slow and weather-dependent, (2) drying/storage facilities must be available for the entire crop, (3) electrical demand of heater may limit system size, (4) grain spoilage results with improper management, (5) harvest moisture contents are generally limited to 26 percent or less (Shove, 1974), and (6) extended drying time prolongs the management period (Brooker et al., 1974).

Drying process

A comprehensive treatment of the principles of grain drying is beyond the scope of this investigation and will not be attempted here. For detailed coverage of grain-drying theory, the reader is referred to Brooker et al. (1974), Henderson and Perry (1955), and Hukill (1974). The discussion of the low-temperature drying process that follows is included as
background for the development of a rationale for process control. Psychometric terms are defined in Appendix A.

Grain, being a hygroscopic material, has an inherent ability to hold moisture. Similarly, air at a given temperature and relative humidity contains a specific amount of moisture. When air is passed through grain, an exchange of water results. At low airflow rates, moisture equilibrium is established between the grain and the air. During drying, the air serves as a medium to supply the energy required for evaporation and to carry the evaporated moisture from the grain.

Initially, the heat of vaporization comes from a decrease in the temperature of both the air and the grain. As drying continues, the exhaust air approaches saturation, and the temperature of the undried grain cools to near the wet-bulb temperature. At this point, all of the drying energy must come from a decrease in air temperature. A temperature gradient is subsequently established across a finite depth of grain. The condition of the air as it passes through this adiabatic "drying zone" follows a wet-bulb line on the psychometric chart. Grain upstream from the drying zone assumes the dry-bulb temperature of the inlet air, while the downstream grain approaches the wet-bulb temperature.

In general, then, three distinct zones may be identified in a bin of grain undergoing low-temperature drying (Shove and Olver, 1967): (1) a dry zone containing grain in equilibrium with the inlet air, (2) an active drying zone moving slowly in the direction of airflow, and (3) a wet zone containing undried grain in equilibrium with the exhaust air. Drying begins near the air inlet and proceeds in the direction of airflow as the drying zone advances through the grain mass (Figure 1).
In practice, the zone stratification and temperature relationships are not as clearly defined as has been suggested. The foregoing discussion assumed inlet air at a constant temperature and relative humidity. Under field conditions, the low-temperature drying process involves broad diurnal cycling of inlet air conditions. These fluctuations give rise to numerous temperature gradients within the grain mass, both increasing and decreasing with respect to direction of airflow. Further, the vapor pressure of the air may be above or below that of the grain in individual layers.

The complex nature of the low-temperature drying process is indicated by Bloome and Shove (1971). They identify four distinct processes possible within the grain mass: (1) cooling of the grain accompanied by drying, (2) cooling of the grain accompanied by wetting, (3) heating of the grain accompanied by drying, and (4) heating of the grain accompanied by wetting. Thus, rewetting, as well as drying, can occur in low-temperature drying.

The low-temperature drying process seldom yields grain with a final moisture content that is uniform throughout the bin. Moisture levels near the top of the grain mass are typically 2 to 3 percent greater than those in the bottom layers (Shove, 1970a). Drying is normally terminated at the desired average moisture content.

**Equilibrium moisture content**

Moisture-bearing cereal grains exhibit a characteristic water vapor pressure at a given temperature and moisture content. This vapor pressure determines whether a grain will desorb (lose) moisture or adsorb (gain) moisture during exposure to moist air. When the vapor pressure of the water held by the grain is equal to the vapor pressure of the enveloping
air, the grain is said to be at its equilibrium moisture content (Brooker et al., 1974). The relative humidity of the surrounding air at this point is termed the equilibrium relative humidity (Henderson and Perry, 1955).

In practice, the equilibrium moisture content and associated equilibrium relative humidity control the moisture content to which grain will dry when exposed to air with a given relative humidity and temperature. Because of the fundamental importance of the equilibrium moisture content in grain drying, moisture content equilibria have been determined experimentally for many grains. Theoretical and empirical models for calculating equilibrium moisture content have also been developed (Brooker et al., 1974).

Plotting equilibrium moisture content against relative humidity, while holding temperature constant, results in a characteristic sigmoid curve called a moisture-sorption isotherm (Hunt and Pixton, 1974). Equilibrium moisture contents referred to in this investigation are taken from moisture desorption isotherms for shelled corn, according to the equation of Chen and Clayton (1970) (Figure 2).

**Hysteresis effect**

In the process of drying, grain loses moisture to the surrounding air until it approaches what is called the desorption equilibrium moisture content. Similarly, dry grain which equilibrates with high-humidity air by gaining moisture (rewetting) is said to have reached its adsorption equilibrium moisture content. For cereal grains, desorption moisture contents are as much as 1.5 to 2.0 percent higher than the adsorption values at
Figure 2. Moisture desorption isotherms for shelled corn. Equation of Chen and Clayton (1970)
Equation of Chen and Clayton (1970)
constant temperature (Hunt and Pixton, 1974). This difference between the desorption and adsorption isotherms is called the hysteresis effect.

The hysteresis effect is complex and not well understood. Although theories have been proposed to explain the phenomenon (Chung and Pfost, 1967), quantitative applications to grain drying remain elusive. For the purposes of this investigation, hysteresis effects involved in grain conditioning will be neglected. Desorption characteristics of shelled corn will be assumed unless otherwise identified.

**Heat of vaporization**

The heat of vaporization of a cereal grain may be defined as the energy required to vaporize a unit amount of moisture from the product. Its magnitude, higher than that for free water, is inversely related to the moisture content and temperature of the grain (Brooker et al., 1974).

Accurate and comprehensive data describing the heat of vaporization of water in grains remain to be fully developed (Hukill, 1974). A working range of 1100 to 1200 Btu per lb of water is commonly used for shelled corn drying applications (Hill and Shove, 1972).

**Allowable storage time**

Wet grain will deteriorate rapidly in storage if held beyond time limits that are governed largely by temperature and moisture content. This "spoilage" is caused by the natural metabolic activity of the grain and the accompanying microflora (Pomeranz, 1974). The microorganisms, comprised primarily of storage fungi (molds), play the greater role (Saul and Lind, 1958).
In low-temperature drying, the moisture content of grain located ahead of the drying zone is not reduced below its initial level until influenced by the advancing drying zone. Grain at the top of the bin remains wet and susceptible to spoilage during most of the total drying period. Thus, the storage time available before spoilage is a crucial factor in low-temperature drying.

The relationship between deterioration rate and the temperature and moisture content of shelled corn has been quantified by the U.S. Department of Agriculture (1968) and Steele et al. (1969). These data are commonly presented as a family of curves indicating allowable storage time as a function of grain temperature and moisture content (Figure 3).

Safe storage periods can be seen to increase markedly as grain temperatures and moisture contents decline. If held within the limits shown, corn will undergo up to 0.5 percent dry matter decomposition but remain acceptable. This allowable deterioration level is based on an empirical correlation between dry-matter loss and damaged kernels. Grain marketing standards require a lowering of grade when damaged kernels exceed one-half of 1 percent by weight (U.S. Department of Agriculture, 1970). The reliability of the allowable-storage-time curves is sometimes questioned (Saul, 1970; Bakker-Arkema et al., 1976). Still, these data provide the best quantitative information available relating temperature and moisture content to storage life.

In addition to grain temperature and moisture content, mechanical damage of individual kernels is known to affect allowable storage time (Steele et al., 1969). Difficulty in making field assessment of mechanical damage has limited quantitative use of this criterion (Schmidt et al.,
Figure 3. Allowable storage time for shelled corn at various temperature and moisture contents. U.S. Department of Agriculture Grain Storage Research Laboratory, Ames, Iowa
Practical guidelines for low-temperature drying recommend that the grain be screened prior to loading to minimize the presence of damaged kernels in the bin (Arnholt and Rupp, 1974; Shove, 1972).

**Aeration**

The use of aeration to maintain the condition of stored grains is accepted practice (Foster and Stahl, 1959). Simply stated, the process consists of ventilating the grain with ambient air to: (1) limit moisture migration by minimizing temperature gradients and (2) inhibit mold growth and insect activity by maintaining a low storage temperature.

During unventilated storage, grain temperatures near the bin wall tend to follow average ambient levels. Temperature gradients develop between the perimeter grain and the grain closer to the center. Convection air currents slowly redistribute moisture from the warmer to the cooler areas. If allowed to continue, this "moisture migration" produces wet-grain zones with high susceptibility to spoilage. Aeration equalizes temperatures within the grain mass and minimizes moisture migration.

As discussed previously, biological activity in stored grain is directly related to grain temperature. Below 50°F, the development of microflora within the grain is restricted significantly (Burrell, 1974). The risk of damage from molds, as well as from stored-grain insects, is reduced greatly by using aeration to maintain low temperatures throughout the bulk. Aeration also serves to remove heat generated by the respiring grain and microorganisms (Agricultural Research Service, 1968).

In low-temperature drying systems, aeration is normally accomplished by periodic operation of the drying fan (Arnholt and Rupp, 1974). If the
time of ventilation is managed selectively, with regard to ambient tempera­ture and relative humidity, aeration can be used to reduce the moisture content of grain still insufficiently dried (Foster, 1967; Converse et al., 1973) or to replace moisture in overdried lower bin layers (Agricultural Research Service, 1968).

Weather Data Analysis

Ambient air is the major energy source in the low-temperature drying process. Drying progress is governed largely by the temperature and mois­ture content of natural air. A control system seeking to automate the process is at a distinct disadvantage because the basic energy input cannot be regulated directly.

A reasonable approach to the problem can be based on expected average weather conditions (Shove, 1970b). For a given location and time of year, future conditions are best estimated through the analysis of past weather records (Notestine and Stewart, 1964; Zachariah and Lipper, 1966).

In this investigation, 28 years of long-term Des Moines, Iowa, weather data were analyzed to establish rational weather-related parameters for the design of controls for low-temperature drying.

Computer analysis

A magnetic tape containing official Des Moines, Iowa, records from the United States Department of Commerce Weather Service was obtained from Dr. T. L. Thompson, Agricultural Engineering Department, University of Nebraska, Lincoln. The data consisted of dry bulb and dew point

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1 National Climatic Center, Asheville, North Carolina.
temperatures at 3-hour intervals for the drying seasons of 1945 through 1972. A computer routine was written to read the data and write it on a second tape in a format compatible with the Iowa State University IBM 360/70 computer system.

A computer program was written to calculate 28-year weekly, biweekly, and monthly arithmetic means for dry-bulb temperature, wet-bulb temperature, dew-point temperature, relative humidity, and shelled-corn equilibrium moisture content. Equations presented by Brooker (1967), Chen and Clayton (1970), and Sun (1971) were used to determine wet-bulb temperature, relative humidity, and equilibrium moisture content, respectively. Standard deviations were also calculated as a measure of the variation of the individual values from the mean (Snedecor, 1956).

Weekly means for the low-temperature drying season for dry-bulb temperature, wet-bulb temperature, relative humidity, and equilibrium moisture content are plotted in Figures 4-7. The dispersion of the data, as defined by ±1 standard deviation from the mean, is indicated by the shaded interval on each graph. Two-thirds of the data were contained within these limits.

A search was conducted for the "average" drying season from among the 28 years analyzed. Average monthly values of dry-bulb temperature, wet-bulb temperature, and relative humidity for September through May of each year were compared with the previously calculated 28-year monthly means. Values that fell within ±1 standard deviation of the long-term means were defined as average. Years containing more than one nonaverage value were rejected. Only one year, 1968, was found to meet the selection criterion. In Figure 8, the 1968 monthly averages for dry-bulb temperature and
Figure 4. Mean dry-bulb temperature for drying season, Des Moines, Iowa. Shaded area indicates ±1 standard deviation.
28-Yr Record; Des Moines, Iowa
Weekly Means, ±1 Std Deviation

MEAN DRY BULB TEMPERATURE (°F)

MONTH

OCT  NOV  DEC  JAN  FEB  MAR  APR  MAY
Figure 5. Mean wet-bulb temperature for drying season, Des Moines, Iowa. Shaded area indicates ±1 standard deviation.
28-Yr Record; Des Moines, Iowa
Weekly Means, ±1 Std Deviation
Figure 6. Mean relative humidity for drying season, Des Moines, Iowa. Shaded area indicates ± standard deviation.
28-Yr Record; Des Moines, Iowa
Weekly Means, ±1 Std Deviation

MEAN RELATIVE HUMIDITY (%)
Figure 7. Mean equilibrium moisture content for drying season, Des Moines, Iowa. Shaded area indicates ± 1 standard deviation. Shelled corn, equation of Chen and Clayton.
28-Yr Record; Des Moines, Iowa
Weekly Means, ± Std Deviation

DIGRAM DESCRIPTION

MONTH: OCT NOV DEC JAN FEB MAR APR MAY
MEAN EQUILIBRIUM MOISTURE CONTENT, CORN (% w.b.)

Graph showing mean equilibrium moisture content for corn in Des Moines, Iowa, over a 28-year record with weekly means and standard deviation.
Figure 8. Average dry-bulb temperature and relative humidity for 1968 drying season. Shaded area indicates $\pm 1$ standard deviation from 28-year means.
28-Yr Record; Des Moines, Iowa
Monthly Means, ±1 Std Deviation
1968 Monthly Averages Indicated
relative humidity are plotted within the interval defined by ± 1 standard deviation from the 28-year means.

Low-Temperature Drying System Design

A typical low-temperature drying system (Figure 1) was chosen for purposes of simulation and evaluation in this investigation. Design specifications were based on current recommendations and guidelines.

**Bin size, airflow rate**

Shove states that "a typical corn drying system employs an airflow rate of 1.25 to 2 cfm per bu through a grain depth of up to 16 feet" (Farm Electrification Council, 1976). For this investigation, a minimum airflow rate of 1.5 cfm per bu was selected for a depth of 16 ft.

A circular steel bin with a diameter of 21 ft was assumed. Bin capacity, at a 16-ft depth, is approximately 4400 bu. Thus, the required full-bin airflow rate is 6600 cfm.

**Fan size**

Fan selection was based on static pressure requirements (Figure 9) and typical fan performance curves (Figure 10). A 7.5-hp vane-axial fan was shown to be adequate.

**Airflow range and fill depths**

Airflow requirements vary directly with initial moisture content. An upper airflow rate of 3 cfm per bu is recommended for corn at 26 percent moisture content (Shove, 1973). For this investigation, airflow rates of 1.5, 2.0, 2.5, and 3.0 cfm per bu were selected.
Figure 9. Static pressure requirements for airflow in shelled corn. Based on a multiplier of 1.5 applied to the data of Shedd (1953).
Figure 10. Typical performance of vane-axial fans
Figure 10. Typical performance of vane-axial fans
AIRFLOW RATE (ft³/min, thousands)

STATIC PRESSURE (in. H₂O)
Typical low-temperature drying systems employ a single, fixed-speed fan. Airflow rate is controlled by varying the depth of fill. Figures 9 and 10 were used to estimate the depth of grain required to obtain the desired airflow rates. Fill depths are shown below:

- 1.5 cfm per bu - 16 ft (4400 bu)
- 2.0 cfm per bu - 13 ft (3850 bu)
- 2.5 cfm per bu - 11 ft (3025 bu)
- 3.0 cfm per bu - 10 ft (2750 bu)

**Selection of temperature rise**

A temperature rise of 2°F to 3°F is normally imparted to the air as it passes through the fan. For this investigation, a temperature rise from the motor and fan of 2°F was assumed.

Recommendations for temperature rise from the heater range from 3°F (Farm Electrification Council, 1976) for 8°F (Arnholt and Rupp, 1974). An appropriate heater temperature rise for central Iowa was determined from an analysis of long-term weather records. A computer program was written to calculate 28-year weekly mean equilibrium moisture contents from the Des Moines weather data. Calculations were based on the equation of Chen and Clayton (1970). The program was then modified to permit the addition of sensible heat to the individual dry-bulb readings. New equilibrium moisture contents were calculated for selected temperature rises.

Results of the calculations are plotted in Figure 11. The effect of the temperature rise from the motor and fan is shown by the 2°F curve. Supplying an additional temperature rise of 3°F lowers the equilibrium moisture content to the mean given by the 5°F curve.
Figure 11. Mean equilibrium moisture content for drying season, Des Moines, Iowa. Curves for air temperature rises of 2°F and 5°F included. Shelled corn, equation of Chen and Clayton (1970)
28-Yr Record
Des Moines, Iowa
Weekly Means

MONTH

OCT  NOV  DEC  JAN  FEB  MAR  APR  MAY

MEAN EQUILIBRIUM MOISTURE CONTENT, CORN (% w.b.)

EMC
EMC (2°F temp. rise)
EMC (5°F temp. rise)
The latter curve shows that, as late as December 15, a 5°F overall temperature rise is sufficient to dry shelled corn to the target moisture content of 15 percent. Overdrying can be expected with a larger rise. A heater temperature rise of 3°F was chosen for this investigation.

**Heater size**

The heater was sized using the following equation:

\[
H_{kW} = \frac{(cfm) (T_r)}{3000} \quad \text{(Shove, 1972)}
\]

Full-bin airflow was assumed, with 1.5 cfm per bu. A minimum heater capacity of 6.8 kw was calculated. In practice, the nearest standard size would be specified.

**Control System Constraints**

In this investigation, the conventional low-temperature drying system described previously will be used to provide process parameters for the control system feasibility study. All equipment and apparatus comprising the drying and control systems will be restricted to conventional, currently available components, in order to pursue the goal of a practical design that can be implemented readily.

**Grain moisture content**

The major dependent variable involved in the low-temperature drying process is the moisture content of the grain. Control of this variable implies that it be measured to return status information to the control system.

Remote determination of moisture content in bulk grain poses difficult problems that remain to be solved (Holtman and Zachariah, 1969).
Several measurement approaches have been suggested including electrical resistance across imbedded sample cells, relative humidity of intergranular air by in situ sensors, and extraction of intergranular air for remote analysis (Gough, 1976). None of the available techniques is as yet practical for field control applications.

The difference between inlet and exhaust air temperatures has been proposed as an indicator of grain moisture content for control of continuous-flow dryers (Agness and Isaacs, 1967). This approach is based on the psychometric result that inlet air cools as it picks up moisture in the drying zone. The resulting temperature gradient between inlet and exhaust air is a measure of the progress of the drying zone (Shove and Olver, 1967).

The suitability of this method of moisture determination for low-temperature drying was evaluated from data recorded in recent field experiments (Kranzler and Bern, 1975). A curve of inlet (plenum) temperature minus exhaust temperature is plotted in the upper portion of Figure 12. The temperature differential ($\Delta T$) is seen to reflect the influence of diurnally cycling inlet temperatures, in addition to the grain moisture content. For low-temperature drying applications, the difference between inlet and exhaust air temperatures would appear to be of little direct value as an indicator of grain moisture content.

**Grain deterioration**

Another important dependent variable is the amount of deterioration, or spoilage, during drying. In laboratory experiments, deterioration may be determined indirectly from the carbon dioxide production of the
Figure 12. Daily plenum and exhaust air temperatures, low-temperature corn drying experiment (Kranzler and Bern, 1975). Airflow rate = 1.0 cfm per bu. Upper curve: $\Delta T =$ plenum temperature minus exhaust temperature.
respiring grain and associated microorganisms (Steele et al., 1969). No practical field equivalent of this technique is available.

**Open-loop control**

Closed-loop control of a process requires that information about the variables to be controlled be fed back to the control system for comparison with desired levels. The lack of suitable sensors for grain moisture content and deterioration minimizes the possibility of closed-loop control of low-temperature drying. An open-loop system, in which desired outputs are predetermined by selectively calibrated input devices, must be considered. Such a control system may rely on "human intervention" for certain decision and correction inputs. The operator, in effect, closes the loop and creates a manual closed-loop control system (Weyrick, 1975).

A manual closed-loop control system is proposed in this investigation. Operator participation is assumed to monitor grain moisture content and deterioration and to halt drying when a satisfactory moisture level has been reached. Some degree of operator involvement is not an unreasonable expectation, since periodic inspection of drying progress and equipment is a wise practice with any drying system.

The use of simple, readily available thermostatic and humidistatic sensors will be assumed to obtain "on-off" control inputs in response to specified levels of ambient and grain conditions. These two-state, discontinuous control signals are directly compatible with digital logic components.
The low-temperature drying process is governed by five independent variables (Bloome and Shove, 1972): (1) airflow rate, (2) harvest moisture content, (3) amount of heat added, (4) harvest date, and (5) prevailing weather conditions. A logical first step in the development of controls for the process is the exploration of the relation between these independent variables and the dependent variables of drying time, final moisture content, and extent of deterioration during drying. Ideally, these relationships should be examined under dynamically varying input conditions resembling those encountered in the field.

Computer simulation permits the above approach to be pursued without the seasonal limitations imposed by field studies. After dependent process variables have been modeled as mathematical functions of the independent variables, a large number of combinations of variables can be evaluated with relative speed and ease. Long-term trends and probabilities can be investigated by inputing many seasons of weather data. By using process modeling and weather data analysis, control parameters can be identified and evaluated.

**Thompson model**

The computer model developed by Thompson (1972) to simulate low-temperature, aerated storage and drying of shelled corn was used in this investigation. A detailed description is presented in Appendix B. Although the "moisture equilibrium" assumption underlying the Thompson simulation has been questioned (Bakker-Arkema et al., 1976), peer acceptance of the model has been favorable (Morey et al., 1971; Flood et al., 1972;
Laboratory verification of the basic model was demonstrated by Thompson et al. (1971). Verification based on field studies, however, has not been reported.

In order to assess the ability of the model to predict field results, low-temperature drying data obtained by Kranzler and Bern (1975) were simulated using 1975 Des Moines weather records. Predicted moisture profiles at the midpoint and end of the drying period are compared with measured experimental levels in Table 1. Excellent agreement is indicated between simulated and actual results. It should be noted that the 18 percent initial moisture content of the 1975 study is lower than would be expected in a "normal" drying season.

Although the Thompson model is designed to accept weather data consisting of 3-hour readings, it may be programmed to average these data over a diurnal period and perform the season simulation using 24-hour average values as input. Significant savings in computer operation time are offered by the latter input format.

A number of simulation runs was conducted to compare the effect of 3-hour and 24-hour input data on simulation accuracy. Differences in results were judged negligible. Simulation work reported by Bakker-Arkema et al. (1976) supports this conclusion. Unless otherwise indicated, computer simulation runs in this investigation were conducted using 24-hour average weather data.

Minimum required airflow

The version of the Thompson model employed in this investigation may be used to automatically compute the minimum airflow rate required for
<table>
<thead>
<tr>
<th>Grain depth (ft)</th>
<th>November 8, 1975</th>
<th>November 15, 1975</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Predicted</td>
<td>Measured</td>
</tr>
<tr>
<td>0-2</td>
<td>18.1</td>
<td>17.2</td>
</tr>
<tr>
<td>2-4</td>
<td>17.1</td>
<td>16.2</td>
</tr>
<tr>
<td>4-6</td>
<td>15.6</td>
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<td>6-8</td>
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<td>14.8</td>
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<td>10-12</td>
<td>13.7</td>
<td>14.6</td>
</tr>
<tr>
<td>12-14</td>
<td>13.8</td>
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</tr>
<tr>
<td>14-16</td>
<td>14.2</td>
<td>14.4</td>
</tr>
<tr>
<td>Average</td>
<td>15.1</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Field results, Kranzler and Bern (1975); Ames, Iowa
1975 weather data; Des Moines, Iowa
Harvest date = October 26, 1975
Harvest moisture = 18% w.b.
Airflow rate = 1.0 cfm/bu
Temperature rise = 6.0°F, total
"successful" drying with a given harvest date, initial harvest moisture content, and temperature rise. Drying success is defined in terms of worst-layer constraints on final moisture content and deterioration, as indicated by dry-matter loss. The limits are programmed at a moisture content of 15 percent and a dry-matter loss of 0.5 percent.

These success criteria relate to official marketing standards for shelled corn (U.S. Department of Agriculture, 1970). Corn is normally traded on the basis of 56 lb of total weight per bushel at 15.5 percent moisture. Grain with a moisture content less than 15.5 percent receives no premium. Thus, marketing at less than 15.5 percent moisture results in selling less weight than allowable. Similarly, corn with a dry-matter loss correlating with kernel damage of up to 0.5 percent may be marketed without penalty.

In arriving at the minimum airflow rate, the program examines the possibility that airflow requirements may be less when fall drying is extended over winter and into spring. In the case of spring completion, continuous aeration and uniform temperature rise are assumed throughout the period.

**Probability of drying success**

In order to establish the probability of drying success with a given set of initial conditions, results with several combinations of independent variables were simulated using 10 years (1960-1969 drying seasons) of Des Moines, Iowa, weather data. For each season, the minimum required airflow rate was calculated for a specific combination of harvest date, harvest moisture content, and air temperature rise. Variables appropriate for
central Iowa conditions were chosen. Numbers were limited by demands on computer time. The values selected were:

- Harvest date = October 15 and November 1
- Harvest moisture = 22, 24, and 26 percent
- Temperature rise = 2 and 5°F

Instant filling of the bin was assumed for all simulation runs. This is the most severe loading condition encountered in the field. Fan and heater operation was held constant. Runs for 22 percent moisture content with a 5°F temperature rise were omitted.

Simulation resulted in 100 datum points of minimum required airflow for successful drying. Results are summarized in Table 2. Wide variation among seasons, with a given set of independent variables, is demonstrated by the fivefold average difference between best-case and worst-case airflow minimums. The extreme nature of the worst-case season is shown by average worst-case minimums twice those of the next-to-worst-case seasons. Repetition of specific best-case and worst-case drying seasons is evident. The previously determined average drying season (1968) is well represented among the median-case results.

For each combination of independent variables and drying season, the calculated minimum airflows were arranged in ascending order (Appendix C). These ranked data are plotted in Figures 13-17 to indicate the probability of drying success as a function of airflow rate. Ninety percent probability levels are identified on each graph to show the predicted minimum airflow rates for drying success in 9 out of 10 drying seasons.

Using a 90 percent probability level as a decision criterion and the previously adopted operational airflow rates, the graphs were used to
Table 2. Summary of simulation results, minimum required airflow for successful drying

<table>
<thead>
<tr>
<th>Harvest date</th>
<th>Harvest per-moisture rise (% (°F, w.b.) total)</th>
<th>Best case</th>
<th>Median case</th>
<th>Next-to-worst case</th>
<th>Worst case</th>
</tr>
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<tbody>
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<td>22 2</td>
<td>0.36^a</td>
<td>0.78</td>
<td>1.32</td>
<td>1.64</td>
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<td></td>
<td></td>
<td>31^b</td>
<td>31</td>
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<td></td>
<td>69^c</td>
<td>68</td>
<td>64</td>
<td>63</td>
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<tr>
<td>Oct. 15</td>
<td>24 2</td>
<td>0.69</td>
<td>1.41</td>
<td>2.18</td>
<td>4.42</td>
</tr>
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<td>05</td>
<td>04</td>
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<td>65</td>
<td>63</td>
</tr>
<tr>
<td>Oct. 15</td>
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<td>04</td>
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<td></td>
<td>67</td>
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<td>63</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>26 5</td>
<td>1.36</td>
<td>2.46</td>
<td>4.05</td>
<td>4.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>07</td>
<td>04</td>
<td>02</td>
<td>03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>66</td>
<td>68</td>
<td>65</td>
<td>63</td>
</tr>
<tr>
<td>Nov. 1</td>
<td>22 2</td>
<td>0.40</td>
<td>0.63</td>
<td>0.92</td>
<td>1.25</td>
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<td></td>
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<td>28</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>69</td>
<td>68</td>
<td>63</td>
<td>64</td>
</tr>
<tr>
<td>Nov. 1</td>
<td>24 2</td>
<td>0.54</td>
<td>0.88</td>
<td>1.08</td>
<td>3.51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27</td>
<td>26</td>
<td>27</td>
<td>07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>69</td>
<td>66</td>
<td>65</td>
<td>63</td>
</tr>
<tr>
<td>Nov. 1</td>
<td>24 5</td>
<td>0.56</td>
<td>0.84</td>
<td>1.10</td>
<td>2.48</td>
</tr>
<tr>
<td></td>
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<td>26</td>
<td>21</td>
<td>24</td>
<td>08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>69</td>
<td>66</td>
<td>65</td>
<td>64</td>
</tr>
<tr>
<td>Nov. 1</td>
<td>26 2</td>
<td>0.93</td>
<td>1.84</td>
<td>2.24</td>
<td>5.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17</td>
<td>20</td>
<td>24</td>
<td>03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>69</td>
<td>66</td>
<td>61</td>
<td>64</td>
</tr>
<tr>
<td>Nov. 1</td>
<td>26 5</td>
<td>0.93</td>
<td>1.69</td>
<td>1.83</td>
<td>3.66</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17</td>
<td>18</td>
<td>23</td>
<td>03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>69</td>
<td>66</td>
<td>61</td>
<td>64</td>
</tr>
</tbody>
</table>

Successful drying: final moisture content ≤ 15% w.b., final dry-matter decomposition ≤ 0.5%
1960-1969 weather data; Des Moines, Iowa
Data from Thompson (1975) included

^aMinimum airflow (cfm/bu).

^bWeeks to dry (no.).

^cDrying season (yr).
Figure 13. Probability of drying success vs. airflow rate for temperature rises of $2^\circ F$ and $5^\circ F$. Harvest date, October 15; harvest moisture, 24 percent
10-Yr Record; Des Moines, Iowa

90% Probability

- Temperature Rise = 2°F
- Temperature Rise = 5°F

Harvest Date = October 15
Harvest Moisture = 24%

PROBABILITY OF SUCCESS (no. years out of 10)

MINIMUM AIRFLOW RATE (cfm/bu)
Figure 14. Probability of drying success vs. airflow rate for temperature rises of 2°F and 5°F. Harvest date, November 1; harvest moisture, 24 percent
10-Yr Record; Des Moines, Iowa

90% Probability

Temperature Rise

Temperature Rise

Harvest Date = November 1
Harvest Moisture = 24%

MINIMUM AIRFLOW RATE (cfm/bu)
Figure 15. Probability of drying success vs. airflow rate for temperature rises of 2°F and 5°F. Harvest date, October 15; harvest moisture, 26 percent.
10-Yr Record; Des Moines, Iowa

90% Probability

Temperature Rise = 2°F
Temperature Rise = 5°F

Harvest Date = October 15
Harvest Moisture = 26%

MINIMUM AIRFLOW RATE (cfm/bu)
Figure 16. Probability of drying success vs. airflow rate for temperature rises of 2°F and 5°F. Harvest date, November 1; harvest moisture, 26 percent
10-Yr Record; Des Moines, Iowa

Temperature Rise = 2°F
Temperature Rise = 5°F

Harvest Date = November 1
Harvest Moisture = 26%

90% Probability
Figure 17. Probability of drying success vs. airflow rate for harvest dates of October 15 and November 1. Temperature rise, 2°F; harvest moisture, 22 percent
10-Yr Record; Des Moines, Iowa

- Harvest Date = November 1
- Harvest Date = October 15
- Temperature Rise = 2°F
- Harvest Moisture = 22%

90% Probability
generate a "truth table" defining successful combinations of the independent variables (Table 3). Curves for 5°F temperature rise were used where an improved probability of drying success was predicted.

Table 3. Truth table, drying success

<table>
<thead>
<tr>
<th>Airflow rate (cfm/bu)</th>
<th>Harvest date</th>
<th>Harvest date</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>October 15</td>
<td>November 1</td>
</tr>
<tr>
<td></td>
<td>Harvest moisture (%)</td>
<td>Harvest moisture (%)</td>
</tr>
<tr>
<td>1.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3.0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

1 = successful, greater than 90% chance of drying success
0 = unsuccessful, less than 90% chance of drying success

**Heater operation**

The probability curves show that for most combinations of independent variables, the 5°F total temperature rise resulting from heater operation offers little advantage over the 2°F rise obtained from the motor and fan alone. Selective operation of the heater is indicated.

A truth table was constructed to specify combinations for which heater operation is advantageous (Table 4). The heater was considered to be "off" for all the unsuccessful drying combinations identified in Table 3. Heater operation was judged desirable for combinations involving the November 1 harvest with moisture contents of 24 and 26 percent, even where unsupported
Table 4. Truth table, heater operation

<table>
<thead>
<tr>
<th>Airflow rate (cfm/bu)</th>
<th>October 15 Harvest moisture (%)</th>
<th>November 1 Harvest moisture (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22</td>
<td>24</td>
</tr>
<tr>
<td>1.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3.0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

1 = heater "on" (enabled)
0 = heat "off" (disabled)

by the probability curves. Priority was given to the greater likelihood of fall completion of drying resulting from the use of supplemental heat.
Advantages of the fall finish over spring completion include greater convenience and flexibility of disposal, lower deterioration risk, and more efficient use of energy inputs.

Completion of drying

In order to predict whether completion of drying will occur in the fall, or be delayed until spring, a second series of drying simulations was conducted. Successful combinations of independent variables were programmed with weather data from the appropriate next-to-worst-case drying season (Table 2). Temperature rises were drawn from Table 4.

The extent of the fall drying season was established from long-term Des Moines, Iowa, weather records. Following the first week in December,
the mean weekly dry-bulb temperature is seen to drop sharply below 32°F (Figure 4). Air at, or below, this temperature has little useful drying potential (Shove, 1971). Further, at this time the weekly mean equilibrium moisture content, assuming a 2°F temperature rise, climbs rapidly above 16 percent (Figure 11).

Thus, the end of the fall drying season in central Iowa can be located early in the second week of December. Using this criterion, the number of weeks to the end of the fall drying season was defined as follows:

October 15 harvest - 8 weeks to finish
November 1 harvest - 6 weeks to finish

Grain was defined as being "dry" when the following criteria were reached:

- Average moisture content = 15 percent or less
- Moisture content of the top layer = 16 percent or less
- Maximum dry-matter loss = 0.5 percent or less

Results from the simulation runs, combined with information from Table 3, are presented in Table 5. This "drydown indicator" table identifies the combinations of initial variables that will yield a predicted 90 percent probability of drying success and indicates whether completion of drying should be expected in the fall or the spring of the year.

**Fan control**

Periods of fog, drizzle, rain, or snow can be expected during the low-temperature drying season. Relative humidities of 90 to 100 percent are common during such weather patterns. Operation of the drying fan during these high-humidity conditions adds moisture to the grain already dried
Table 5. Drydown indicator

<table>
<thead>
<tr>
<th>Airflow rate (cfm/bu)</th>
<th>October 15</th>
<th></th>
<th>October 15</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Harvest moisture (%)</td>
<td></td>
<td>Harvest moisture (%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>24</td>
<td>26</td>
<td>22</td>
</tr>
<tr>
<td>1.5</td>
<td>F</td>
<td>U</td>
<td>U</td>
<td>F</td>
</tr>
<tr>
<td>2.0</td>
<td>F</td>
<td>U</td>
<td>U</td>
<td>F</td>
</tr>
<tr>
<td>2.5</td>
<td>F</td>
<td>F</td>
<td>U</td>
<td>F</td>
</tr>
<tr>
<td>3.0</td>
<td>F</td>
<td>F</td>
<td>U</td>
<td>F</td>
</tr>
</tbody>
</table>

U = unsuccessful, less than 90% chance of drying success
F = fall finish, drying completed in the fall
S = spring finish, drying completed in the spring

(Bloome and Shove, 1971). The shelled-corn equilibrium moisture content for air at 40°F and 90 percent relative humidity, for example, is approximately 22 percent (Figure 2). Extra drying energy and time are required to remove adsorbed moisture from the rewetted grain.

Early in the drying period rewetting is of only moderate concern. Humid intake air gains drying potential as it loses moisture to the dry grain in the bottom layers (Hukill, 1961). Drying continues slowly in the wetter layers above.

Later in the drying season, however, rewetting becomes a growing liability. Drying, even in the upper layers, is slowed or stopped during extended periods of high humidity. Falling average daily temperatures and increasing average relative humidity reduce the natural drying potential available to remove moisture adsorbed during rewetting. Additional
operating time is required to dry the grain to the desired final moisture content.

Three approaches to the problem of rewetting are available: (1) rewetting may simply be accepted, with the accompanying penalty in drying energy and time, (2) rewetting may be minimized by adding sufficient heat to the air to lower the relative humidity to an acceptable level, and (3) rewetting may be minimized by interrupting the airflow during periods of high relative humidity.

Present practice follows the first approach. Heaters are sized on the basis of average Corn Belt weather conditions (Farm Electrification Council, 1976). Continuous operation is recommended during periods of inclement weather (Shove, 1972, 1973). Reduced drying efficiency is accepted as a necessary evil, in order to simplify management and system requirements.

A temperature rise of approximately 10°F is needed to prevent rewetting when relative humidities approach 100 percent (Farm Electrification Council, 1976). For the low-temperature drying system of this investigation, extra heater capacity of almost triple the specified size would be required during humid weather. A substantial increase in energy consumption and equipment costs would result.

In order to explore the possible reduction of extra energy requirements associated with rewetting, the feasibility of controlling fan operation during periods of high humidity was investigated.

Early in the drying period, when the grain moisture content and average ambient temperature are relatively high, continuous aeration is required to control spontaneous heating arising from respiration. As
drying proceeds and outside air temperatures cool, the risk of spoilage from biological activity decreases steadily.

Eventually, a point is approached at which fan operation can be interrupted for short periods without jeopardizing allowable storage time. Having reached this point, humidistatic control of fan operation becomes feasible to prevent rewetting during hours of high relative humidity. The need arises for identifying the onset of this "safe" temporary shutoff time in the drying period. Temperature and moisture-content criteria for determining the safe intermittent aeration point were considered.

The risk of spoilage is known to decrease markedly with temperature. Burrell (1974) states that the development of microflora is "exceedingly slow" at temperatures below 50°F. Brooker et al. (1974) observe that the rate of respiration of grain and of the microorganisms present is "reduced substantially" as the temperature drops below 40°F. For the purposes of this investigation, 45°F was chosen as the target temperature. Intermittent fan operation was disallowed at grain temperatures of 45°F or greater.

Flood et al. (1972), assuming late-fall air temperatures between 40°F and 50°F, used the 18 percent moisture level as a criterion for successful drying. The curves for allowable storage time (Figure 3) show the spoilage risk for corn at 18 percent moisture content to be very low. If the low-temperature corrections of Saul (1970) are applied, reasonable safety is indicated for grain at up to 22 percent moisture and 45°F.

In order to predict the number of weeks in the drying period preceding the safe intermittent-aeration point, a third series of drying simulations was conducted using 1968 "average" weather data with the previous
combinations of initial conditions. The following decision criteria were used for each simulation run:

- Average grain moisture content $\leq$ 18 percent
- Moisture content of top layer $\leq$ 22 percent
- Temperature of top layer $\leq$ 45°F

Results of the simulation series are presented in Table 6. For each set of independent variables, the table gives the predicted average safe delay time in weeks before humidstatic control of fan operation can be enabled. A humidistat "inhibit" is specified for each of the previously defined unsuccessful combinations.

Table 6. Time delay before humidistat enable

<table>
<thead>
<tr>
<th>Harvest date</th>
<th>October 15</th>
<th>November 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow rate (cfm/bu)</td>
<td>Harvest moisture (%)</td>
<td>Harvest moisture (%)</td>
</tr>
<tr>
<td>22</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>1.5</td>
<td>2</td>
<td>I</td>
</tr>
<tr>
<td>2.0</td>
<td>2</td>
<td>I</td>
</tr>
<tr>
<td>2.5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3.0</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

2 = two weeks
3 = three weeks
4 = four weeks
5 = five weeks
I = humidistat inhibit
1968 weather data; Des Moines, Iowa
The frequency of occurrence of ambient conditions favoring fan interruption was estimated by conducting an analysis of 10 years of Des Moines weather data. A computer program was written to identify weather periods of 3 hours, or longer, with ambient conditions as follows:

Relative humidity $\geq 90$ percent

Dry bulb temperature $\leq 45^\circ F$

A summary of results is given in Table 7. The data show that, between November 1 and December 15, an average total of 107 hours meeting the above criteria can be expected. This average is equal to 10 percent of the overall period. Spring occurrences average 59 total hours and represent 8 percent of the period (March 16-April 15).

Table 7. Occurrence of relative humidity $\geq 90\%$, temperature $\leq 45^\circ F$

<table>
<thead>
<tr>
<th>Average (hours)</th>
<th>November</th>
<th>December</th>
<th>March</th>
<th>April</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-30</td>
<td>1-15</td>
<td>16-31</td>
<td>1-15</td>
</tr>
<tr>
<td>Monthly</td>
<td>57</td>
<td>50</td>
<td>58</td>
<td>62</td>
</tr>
<tr>
<td>Fall total</td>
<td>107</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Duration of individual occurrence $\geq 3$ hours
1960-1969 weather data; Des Moines, Iowa
Heater control

A review of Figure 2 will show that, at low-to-moderate relative humidities, supplemental heat is not required to dry grain to an acceptable terminal moisture content. For example, air at 40°F and 60 percent relative humidity yields an equilibrium moisture content of less than 15 percent.

Operation of the heater during these "dry" intervals increases the drying rate slightly but also results in overdrying and unnecessary consumption of electrical energy. The latter factors suggest the desirability of humidistatic control to interrupt heater operation when the relative humidity falls below a specified level.

The past incidence of low-humidity weather conditions was studied to predict the number of hours during which heater operation is not required. A computer program was written to scan 10 years of the Des Moines weather data for the occurrence of relative humidities equal to, or less than, 60 percent.

Summarized results are presented in Table 8. The 10-year sample indicates that an average of 450 total hours with a relative humidity at, or below, 60 percent can be expected between October 16 and December 15. This average is 31 percent of the overall fall drying period. Spring hours meeting the relative humidity criterion total an average of 247 and represent 34 percent of the period (March 16-April 15).

Aeration control

Aeration is required to maintain the condition of grain stored over winter. Periodic ventilation with outside air greatly reduces the risk of
Table 8. Occurrence of relative humidity ≤ 60%

<table>
<thead>
<tr>
<th></th>
<th>October</th>
<th>November</th>
<th>December</th>
<th>March</th>
<th>April</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-15</td>
<td>16-31</td>
<td>1-30</td>
<td>1-15</td>
<td>16-31</td>
</tr>
<tr>
<td>Monthly</td>
<td>129</td>
<td>157</td>
<td>203</td>
<td>89</td>
<td>50</td>
</tr>
<tr>
<td>Fall total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1960-1969 weather data; Des Moines, Iowa

deterioration resulting from biological activity and moisture migration within the grain mass. Aeration must be managed carefully to achieve the desired results, particularly when partly dried grain is being maintained. Ambient conditions of temperature and relative humidity must be considered, as well as the duration and frequency of aeration periods.

The equilibrium moisture content associated with the ambient temperature and relative humidity determines whether drying or rewetting will occur during an aeration period. It is desirable to limit the initiation of aeration to ambient conditions with an equilibrium moisture content close to the average moisture content of the grain.

A lower ambient temperature limit of 30°F is recommended to avoid blockage and spoilage problems that may arise from aggregate freezing of the grain (Noyes, 1967; Holmes, 1973; Brooker et al., 1974). An upper limit of 40°F is suggested to maintain grain temperatures at a level restrictive to the growth of microorganisms (Brooker et al., 1974).
Recommended upper relative humidity limits for aeration range from 60 to 80 percent (Elder, 1971; Holman, 1960). For a 70 percent upper limit, along with 30 to 40°F temperature limits and a 2°F fan temperature rise, the worst-case equilibrium moisture content is approximately 16 percent. Expected average equilibrium moisture contents would be lower.

Operation of the fan, when the ambient temperature differs from the temperature of the grain, causes cooling or warming zones to form and advance through the grain. In the case of warming, moisture may condense at the interface between the leading edge of the zone and the cooler grain above. The resulting "wetted" layer is highly vulnerable to spoilage. To avoid this condition during aeration, it is recommended that fan operation, once initiated, be continuous until the entire zone has moved through the grain column (Noyes, 1967; Brooker et al., 1974).

The upward progress of the temperature-transition zone is governed by the rate of airflow and the duration of the aeration period (Sorenson et al., 1967). For a given airflow rate, the length of the aeration period should be sufficient to permit the passage of both the leading and trailing edges of the zone.

In this investigation, the required aeration period was estimated from data obtained in low-temperature drying field experiments (Kranzler and Bern, 1975). Typical inlet (plenum) and exhaust air temperatures recorded in the study were plotted in Figure 12. The temperature curves show that roughly 12 hours are required for inlet highs and lows to be reflected in the exhaust air readings. For an experimental airflow rate of 1.0 cfm per bu, the temperature-transition zone is seen to move through the grain column in approximately 12 hours.
From the above results, a 12-hour aeration time was judged adequate for the airflow rates specified in this investigation. This aeration period is compatible with the recommendations of Shove (1973).

While aeration within restricted limits of ambient temperature and relative humidity assures a minimum of rewetting, qualifying ambient conditions may occur too infrequently to provide adequate hours of aeration. In order to determine the availability of selected aeration conditions in central Iowa, long-term weather records for November through April were analyzed. A computer program was written to scan 10 years of the Des Moines weather data for days with one, or more, occurrence of the following conditions:

\[30^\circ F \leq T_{\text{amb}} \leq 40^\circ F, \quad RH_{\text{amb}} \leq 75\text{ percent}\]

Diurnal temperature patterns were also considered in the determination of criteria for the start of an aeration period. Declining afternoon temperatures minimize the possibility of overheating the grain during the fixed-length aeration. The feasibility of restricting initiation to afternoon hours was evaluated. The computer program was modified to add a time requisite of 12 pm to 12 am to the above occurrence criteria.

Results of the occurrence analyses are given in Figure 18. Average monthly occurrence days during the aeration season are shown. The restriction on time of day is seen to reduce the number of occurrence days by less than 6 percent. In both cases, the minimum average number of occurrence days available exceeds seven per month. This number appears adequate to meet the recommended aeration frequency of one 12-hour period every 7 to 10 days (Shove, 1973).
Figure 18. Occurrence of conditions satisfying primary aeration criteria
For this investigation, the following criteria were selected for the initiation of a 12-hour aeration period:

\[ 30 ^\circ F \leq T_{\text{amb}} \leq 40 ^\circ F \]
\[ RH_{\text{amb}} \leq 75 \text{ percent} \]
\[ 12 \text{ pm} - 12 \text{ am} \]

An operating scheme for the dry-grain aeration cycle was adopted as follows:

1. A 12-hour aeration period is initiated by an occurrence of the aeration criteria.

2. Following an aeration, further aerations are disallowed for a period of 7 days.

3. Aerations are enabled after the 7-day wait period.

Computer modeling was used to evaluate the performance of the dry-grain aeration control scheme over 10 seasons of the Des Moines weather data for December through March. A computer program was developed to simulate the pattern of fan control in response to seasonal fluctuations of temperature and relative humidity.

Average values of dry-bulb temperature and relative humidity were calculated for each simulated 12-hour aeration. Date and starting time of each aeration were recorded. A typical seasonal record for the dry-grain aeration cycle is shown in Table 9.

Extremes in average conditions during individual aerations were noted. Average aeration temperatures, over the 10 years studied, ranged from 18.0 to 46.3\(^\circ\) F. The range of average relative humidities was 28.4 to 89.3 percent.

Extended periods with temperatures and/or relative humidities outside of the aeration limits were observed. The longest continuous period
Table 9. Typical season simulation, dry aeration cycle

<table>
<thead>
<tr>
<th>Date of aeration (mo-day-yr)</th>
<th>Average, 12-hour aeration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry-bulb temperature (°F)</td>
</tr>
<tr>
<td>12-02-65</td>
<td>34.5</td>
</tr>
<tr>
<td>12-13-65</td>
<td>33.5</td>
</tr>
<tr>
<td>12-21-65</td>
<td>35.0</td>
</tr>
<tr>
<td>12-31-65</td>
<td>37.5</td>
</tr>
<tr>
<td>01-09-66</td>
<td>30.5</td>
</tr>
<tr>
<td>02-11-66</td>
<td>31.5</td>
</tr>
<tr>
<td>02-23-66</td>
<td>26.0</td>
</tr>
<tr>
<td>03-07-66</td>
<td>28.0</td>
</tr>
<tr>
<td>03-19-66</td>
<td>38.8</td>
</tr>
<tr>
<td>03-27-66</td>
<td>36.0</td>
</tr>
<tr>
<td>Season average</td>
<td>33.1</td>
</tr>
</tbody>
</table>

1965 weather data, December 1-March 31; Des Moines, Iowa

without aeration was 40 days. Average temperature and relative humidity during this interval were 30.4°F and 83.7 percent, respectively. Temperature extremes were -8.6 and 36.4°F. The range of relative humidities was 58.2 to 100 percent.

A summary of the dry-grain aeration simulations is presented in Table 10. Season averages for temperature, relative humidity, and hours of aeration are given. Calculated average equilibrium moisture contents include a 2°F fan temperature rise.

A seasonal range of equilibrium moisture contents (13.3 to 15.8 percent) and the 10-year mean equilibrium moisture content (14.9 percent) indicate that the dry-grain aeration scheme will maintain the grain moisture content near the desired 15 percent level. Further, improved
Table 10. Simulation summary, dry aeration cycle

<table>
<thead>
<tr>
<th>Drying season</th>
<th>Dry-bulb temperature (°F)</th>
<th>Relative humidity (%)</th>
<th>Total aeration time (hr)</th>
<th>Equilibrium moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960</td>
<td>31.3</td>
<td>69.3</td>
<td>168</td>
<td>15.6</td>
</tr>
<tr>
<td>1961</td>
<td>29.7</td>
<td>68.4</td>
<td>96</td>
<td>15.4</td>
</tr>
<tr>
<td>1962</td>
<td>33.8</td>
<td>70.4</td>
<td>96</td>
<td>15.4</td>
</tr>
<tr>
<td>1963</td>
<td>32.6</td>
<td>62.7</td>
<td>144</td>
<td>14.3</td>
</tr>
<tr>
<td>1964</td>
<td>31.8</td>
<td>70.5</td>
<td>132</td>
<td>15.8</td>
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<td>1965</td>
<td>33.1</td>
<td>65.4</td>
<td>120</td>
<td>14.7</td>
</tr>
<tr>
<td>1966</td>
<td>32.3</td>
<td>66.0</td>
<td>108</td>
<td>15.0</td>
</tr>
<tr>
<td>1967</td>
<td>31.9</td>
<td>55.4</td>
<td>156</td>
<td>13.3</td>
</tr>
<tr>
<td>1968</td>
<td>31.7</td>
<td>67.5</td>
<td>108</td>
<td>15.1</td>
</tr>
<tr>
<td>1969</td>
<td>31.5</td>
<td>62.5</td>
<td>132</td>
<td>14.3</td>
</tr>
<tr>
<td>Mean</td>
<td>31.9</td>
<td>65.8</td>
<td>126</td>
<td>14.9</td>
</tr>
</tbody>
</table>

Equilibrium moisture contents include 2°F fan temperature rise December 1-March 31 weather data; Des Moines, Iowa

Uniformity in final grain moisture content can be expected to result, as the gradient present at the end of fall drying is influenced by the average equilibrium moisture content for the aeration hours. Finally, a mean aeration time of 126 hours is shown. Expressed on a monthly basis, this total represents 31.5 hours of fan operation, or 2.6 12-hour aeration hours per month. Additional aeration time is called for should grain temperatures reach 45°F or greater.

Partly dried grain being held through winter for spring completion of conditioning requires greater aeration care than fall-dried grain. The dry-grain aeration simulation results showed that prolonged periods may be expected when ambient conditions fall to meet the specified aeration
criteria. Lack of ventilation of moist grain during such intervals entails a growing risk of deterioration as a result of biological activity and thermally driven moisture migration within the grain mass.

A backup, or secondary, aeration period is potentially desirable to minimize the spoilage danger by cooling and equalizing grain temperatures. Because ambient conditions are outside of the desired primary aeration limits, this secondary aeration should be of short duration to avoid extensive freezing and/or rewetting.

Criteria for the initiation of a secondary aeration period were considered. Two approaches are possible. First, the secondary aeration may simply be "forced," following an allowable number of consecutive days without a primary aeration. Computer simulation of this procedure revealed that forced aerations occurred frequently during periods with unacceptable temperature extremes.

A second procedure involves expansion of the aeration limits to increase the probability of occurrence for secondary aerations. After a given number of days with ambient conditions failing to meet the primary aeration criteria, the aeration limits are altered to permit a secondary aeration under relaxed ambient restrictions. Computer simulation of this method proved encouraging and led to the adoption of the following secondary aeration limits:

\[ 15^\circ F \leq T_{\text{amb}} \leq 45^\circ F \]

No restrictions on relative humidity or time of day were specified.

For adequate grain temperature equalization, it was assumed that the secondary aeration period need only be of sufficient length to push the
leading edge of the aeration zone through the grain. Using the lowest
design airflow rate, 1.5 cfm per bu, the minimum time required to move the
forward edge of the zone through the grain was determined from:

\[ T_L = 3.9Q^{-0.94} \]  
(Sorenson et al., 1967)

The calculated minimum time was 2.7 hours. For this investigation, the
length of the secondary aeration period was set at 3 hours.

The frequency of aeration was considered in relation to estimated ven­
tilation requirements and average ambient condition. An operating scheme
for the wet-grain aeration cycle was adopted as follows:

1. A 12-hour aeration period is initiated by an occurrence of condi­
tions within the primary aeration limits.

2. Following a primary aeration, further aerations are disallowed for
   a period of 5 days.

3. Primary aerations are enabled after the 5-day wait period.

4. The absence of primary aeration conditions within 2 days of the
   wait period enables the secondary aeration limits.

5. A 3-hour aeration period is initiated by an occurrence of condi­
tions within the secondary aeration limits.

6. Following a secondary aeration, primary aeration limits are
   enabled.

7. The absence of primary aeration conditions within 5 days of a
   secondary aeration enables the secondary aeration limits.

8. Grain temperatures of 45°F, or greater, override aeration
   sequences and force operation of the fan for cooling.

Computer modeling was used to evaluate the performance of the wet­
grain aeration control scheme over 10 seasons of the Des Moines weather
data for December through March. A computer program was developed to simulate the pattern of fan control in response to seasonal fluctuations of temperature and relative humidity.

Average values of dry-bulb temperature and relative humidity were calculated for each simulated primary (12-hour) and secondary (3-hour) aeration. Date and starting time of each aeration were recorded. A typical seasonal record for the wet-grain aeration cycle is shown in Table 11.

Table 11. Typical season simulation, wet aeration cycle

<table>
<thead>
<tr>
<th>Date of aeration (mo-day-yr)</th>
<th>Average, 12-hour aeration</th>
<th>Average, 3-hour aeration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry-bulb temperature (°F)</td>
<td>Relative humidity (%)</td>
</tr>
<tr>
<td>12-03-68</td>
<td>32.5</td>
<td>72.3</td>
</tr>
<tr>
<td>12-09-68</td>
<td>34.0</td>
<td>46.3</td>
</tr>
<tr>
<td>12-16-68</td>
<td>26.8</td>
<td>46.6</td>
</tr>
<tr>
<td>12-26-68</td>
<td>34.0</td>
<td>46.3</td>
</tr>
<tr>
<td>01-05-69</td>
<td>30.8</td>
<td>74.3</td>
</tr>
<tr>
<td>01-13-69</td>
<td>22.0</td>
<td>74.8</td>
</tr>
<tr>
<td>01-14-69</td>
<td>31.0</td>
<td>70.6</td>
</tr>
<tr>
<td>02-04-69</td>
<td>35.5</td>
<td>67.3</td>
</tr>
<tr>
<td>02-10-69</td>
<td>26.8</td>
<td>71.4</td>
</tr>
<tr>
<td>02-16-69</td>
<td>34.3</td>
<td>71.5</td>
</tr>
<tr>
<td>03-05-69</td>
<td>33.5</td>
<td>74.6</td>
</tr>
<tr>
<td>03-12-69</td>
<td>25.0</td>
<td>68.8</td>
</tr>
<tr>
<td>03-20-69</td>
<td>39.0</td>
<td>42.3</td>
</tr>
<tr>
<td>03-21-69</td>
<td>36.0</td>
<td>64.5</td>
</tr>
<tr>
<td>Season average</td>
<td>32.1</td>
<td>64.5</td>
</tr>
</tbody>
</table>

1968 weather data, December 1 - March 31; Des Moines, Iowa
Extremes in average conditions during individual aerations were noted. For the primary aerations, average aeration temperatures ranged from 19.5 to 41.0°F. The range of relative humidities was 28.4 to 89.4 percent. Average temperatures during secondary aerations ranged from 15.0 to 45.0°F. Relative humidities varied from 30.3 to 99.0 percent.

The longest continuous period with ambient conditions outside of the primary aeration limits was 36 days. Three secondary aerations were recorded during this interval. The longest continuous period without aeration was 16 days.

A summary of the wet-grain aeration simulations is presented in Table 12. Season temperature and relative humidity averages are given for primary and secondary aerations. Weighted averages for temperature, relative humidity, and equilibrium moisture content are presented for combined aerations. Calculated equilibrium moisture contents include a 2°F fan temperature rise.

The seasonal range of equilibrium moisture contents (13.6 to 16.2 percent) and the 10-year mean equilibrium moisture content (15.0 percent) indicate that the wet-grain aeration scheme offers significant assistance in lowering the moisture content of the grain during the aeration season. Mean aeration time for combined aerations was 172 hours. This total represents 43 hours of fan operation per month. Additional aeration time is called for, should grain temperatures reach 45°F or greater.

As spring approaches and average temperatures rise above freezing, the winter aeration schedule can be suspended. For grain that was dried in the fall, the drying system may be shut down or the aeration limits changed to warm the grain for spring sale. Drying can be resumed for grain not yet at
Table 12. Simulation summary, wet aeration cycle

<table>
<thead>
<tr>
<th>Drying season</th>
<th>Season average, 12-hour aerations</th>
<th>Season average, 3-hour aerations</th>
<th>Season average, combined aerations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry-bulb temp (°F)</td>
<td>Relative humidity (%)</td>
<td>Dry-bulb temp (°F)</td>
</tr>
<tr>
<td>1960</td>
<td>34.5</td>
<td>63.1</td>
<td>28.8</td>
</tr>
<tr>
<td>1961</td>
<td>28.5</td>
<td>68.6</td>
<td>24.3</td>
</tr>
<tr>
<td>1962</td>
<td>33.0</td>
<td>66.9</td>
<td>26.1</td>
</tr>
<tr>
<td>1963</td>
<td>32.5</td>
<td>63.6</td>
<td>29.0</td>
</tr>
<tr>
<td>1964</td>
<td>31.7</td>
<td>70.2</td>
<td>26.3</td>
</tr>
<tr>
<td>1965</td>
<td>32.7</td>
<td>71.1</td>
<td>30.0</td>
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<tr>
<td>1966</td>
<td>32.4</td>
<td>68.8</td>
<td>25.7</td>
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<td>1967</td>
<td>32.9</td>
<td>55.8</td>
<td>27.3</td>
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<tr>
<td>1968</td>
<td>32.1</td>
<td>64.5</td>
<td>27.1</td>
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<tr>
<td>1969</td>
<td>33.5</td>
<td>58.6</td>
<td>21.2</td>
</tr>
<tr>
<td>Mean</td>
<td>32.4</td>
<td>65.1</td>
<td>26.6</td>
</tr>
</tbody>
</table>

Equilibrium moisture contents include 2°F fan temperature rise
December 1 - March 31 weather data; Des Moines, Iowa
the safe moisture content when average daily temperatures remain above 35°F (Arnholt and Rupp, 1974). In central Iowa, this condition can be expected about March 15 (Figure 4).

If a control system is to exit from the aeration mode automatically, it should be able to detect or estimate when average daily temperatures exceed a given level. For the control system employing simple "on-off" thermostatic sensors, this determination might be approximated from the presence of a threshold temperature representative of the target daily average.

An analysis of 10 years of the Des Moines weather data for February and March was used to test the feasibility of the above approach. A computer program was written to search for an "indicator" temperature which might correlate with an average daily temperature equal to, or greater than, 35°F. The occurrence of two consecutive days with a high temperature equal to, or greater than, 45°F was found to be a reliable indicator of average daily temperatures of 35°F or greater.

In the 10 seasons of data analyzed, no instances of an average daily temperature equal to, or less than, 34°F were incorrectly identified as 35°F, or greater, by the indicator criterion. Only one occurrence of an average daily temperature equal to, or greater than, 36°F was incorrectly identified. The highest daily average that did not include a temperature of 45°F, or greater, was 42°F.

The occurrence of two consecutive days with a high temperature of 45°F, or greater, appears to be a satisfactory indicator of average daily temperatures equal to, or greater than, 35°F. Such an indicator is readily
detected by a simple thermostat. This criterion was adopted for the control system of this investigation to signal the end of the aeration mode.

Control System

A proposed control system for low-temperature drying, based on the control rationale developed in this investigation, is diagrammed in Figure 19. Brief functional descriptions of individual logic modules are given below.

Initialization matrix

The control system is initialized for a particular set of starting conditions by dialing settings for harvest date (Oct. 15, Nov. 1), harvest moisture content (22, 24, and 26 percent), and airflow rate (1.5, 2.0, 2.5, and 3.0 cfm per bu). On the basis of internally programmed long-term simulation results (Table 13), the control system:

1. Actuates drydown indicator lights on control panel to signal whether the combination of independent variables selected will result in a 90 percent, or better, probability of drying success, and whether completion of drying can be expected in the fall or spring. Combinations yielding less than 90 percent probability of success lock out system operation.

2. Presets counter for programmed delay period before humidistatic fan control is enabled.

3. Enables or disables heater, as programmed.
Figure 19. Block diagram of control system for low-temperature drying
Table 13. Initialization matrix

<table>
<thead>
<tr>
<th>Airflow rate (cfm/bu)</th>
<th>Harvest date</th>
<th>Harvest moisture (%)</th>
<th>Control function</th>
<th>Harvest date</th>
<th>Harvest moisture (%)</th>
<th>Control function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>October 15</td>
<td>22</td>
<td>D C H</td>
<td>November 1</td>
<td>22</td>
<td>D C H</td>
</tr>
<tr>
<td>1.5</td>
<td>D H U I</td>
<td>F 2</td>
<td>F 2 H</td>
<td>D H U I</td>
<td>F 2</td>
<td>F 3 H</td>
</tr>
<tr>
<td>2.0</td>
<td>D H U I</td>
<td>F 2</td>
<td>F 2 H</td>
<td>D H U I</td>
<td>F 2</td>
<td>F 3 H</td>
</tr>
<tr>
<td>2.5</td>
<td>D H U I</td>
<td>F 2</td>
<td>F 2 H</td>
<td>D H U I</td>
<td>F 2</td>
<td>F 2 H</td>
</tr>
<tr>
<td>3.0</td>
<td>D H U I</td>
<td>F 2</td>
<td>F 2 H</td>
<td>D H U I</td>
<td>F 2</td>
<td>F 3 H</td>
</tr>
</tbody>
</table>

Function definitions:

1. D: drydown indicator
   - $D_U$: unsuccessful, less than 90% chance of drying success
   - $D_F$: fall finish, drying completed in the fall
   - $D_S$: spring finish, drying completed in the spring

2. C: counter preset; weeks of drying prior to humidistat enable
   - $C_2$: two weeks
   - $C_3$: three weeks
   - $C_4$: four weeks
   - $C_5$: five weeks
   - $C_I$: counter inhibit

3. H: heater enable
   - $H$: heater enable
   - $H$: not heater enable (disable)
Drying mode, fan control

A flow diagram of the humidistatic fan control logic is presented in Figure 20. Sequential operation is as follows:

1. At the start of drying, the counter is loaded automatically with the programmed time delay period.
2. Following the preset number of weeks, a close-on-rise humidistat is enabled.
3. Fan operation is halted to limit rewetting when ambient relative humidity reaches, or exceeds, 90 percent for a period of 3 hours or greater.
4. Sequence is interrupted at any time by:
   (a) grain temperature equal to, or greater than, 45°F; as signaled by series-connected, close-on-rise thermostats spaced vertically in the center and/or southwest quadrant of the grain mass,
   (b) aeration control switch in "wet" or "dry" position, and
   (c) grain temperature equal to, or less than, 35°F; as signaled by two series-connected, close-on-fall thermostats positioned near the top center and bottom center of the grain mass.

Drying mode, heater control

A flow diagram of the humidistatic heater control logic is presented in Figure 21. Sequential operation is as follows:

1. At the start of drying, heater is enabled or disabled automatically by the initialization logic.
Figure 20. Flow diagram, drying mode. Humidistatic control of fan
Figure 21. Flow diagram, drying mode. Humidistatic control of heater
START

HEATER ENABLED?

YES

RH ≤ 60%?

YES

SWITCH HEATER OFF

NO

SWITCH HEATER ON
2. If enabled, heater is switched off during periods of ambient relative humidity equal to, or less than, 60 percent; as signaled by a close-on-fall humidistat.

**Exit from drying mode**

A flow diagram of the logic governing exit from the drying mode (entry to aeration mode) is presented in Figure 22. Sequential operation is as follows:

1. If enabled, heater is disabled for aeration mode.
2. Aeration control switch is monitored by the control system.
3. If switch is in "dry" position, dry-grain aeration cycle is enabled.
4. If switch is in "wet" position, wet-grain aeration cycle is enabled.
5. If switch is left in "off" position, system maintains drying mode until grain temperature of 35°F, or less, is signaled. System assumes grain is not yet dry and enables wet-grain aeration cycle, automatically.

**Aeration mode**

A flow diagram of the aeration mode logic is presented in Figure 23. Individual operating schemes for the dry-grain aeration cycle and the wet-grain aeration cycle have been detailed previously in the development of aeration control parameters. Overall operation is as follows:

1. Dry-grain aeration cycle or wet-grain aeration cycle is initiated in exit from drying mode.
Figure 22. Flow diagram, exit from drying mode. Entry to aeration mode
Figure 23. Flow diagram, aeration mode. Wet-grain aeration cycle, dry-grain aeration cycle
EVENT Y:
$30^\circ F \leq T_{\text{amb}} \leq 40^\circ F$
$\text{RH}_{\text{amb}} \leq 75\%$
12 pm - 12 am

EVENT Z:
$15^\circ F \leq T_{\text{amb}} \leq 45^\circ F$
2. Primary (12-hour) aerations are initiated by signal from high-low thermostat (30-40°F) and close-on-fall humidistat (75 percent) connected in series.

3. Secondary (3-hour) aerations are initiated by signal from high-low thermostat (15-45°F).

4. Sequence is interrupted at any time by:
   (a) grain temperature equal to, or greater than, 45°F, and
   (b) automatic or manual disabling of aeration mode.

**Exit from aeration mode**

A flow diagram of the logic governing the exit from the aeration mode (system halt) is presented in Figure 24. Sequential operation is as follows:

1. Presence of average daily temperatures equal to, or greater than, 35°F is derived from the occurrence of two consecutive daily high temperatures of 45°F or greater. Peak temperature signals are obtained from close-on-rise thermostat.

2. If dry-grain aeration cycle preceded exit, control system shuts down operation.

3. If wet-grain aeration cycle preceded exit, control system disables 45°F grain temperature sensors and enters drying mode to complete conditioning of grain. Automatic wet-grain aeration option is maintained.

4. Drying continues until halted by manual shutoff.
Figure 24. Flow diagram, exit from aeration mode. System halt
START

AVG. DAILY TEMPERATURE \(\geq 35^\circ\text{F}\) ?

YES

AERATION CYCLE ?

WET

DISABLE GRAIN TEMP. SENSORS

ENTER DRYING MODE

MANUAL SHUTOFF ?

YES

SYSTEM HALT

NO
Fan alarm logic

A flow diagram of the fan alarm logic is presented in Figure 25. Sequential operation is as follows:

1. Fan-enable signal zeros the counter and enables the 1-Hz clock.
2. Counting proceeds until halted by sail switch signal indicating fan is up to speed.
3. If no signal is received within 5 seconds, alarm is set.
4. If fan operation halts while fan-enable signal is present, alarm is set.
5. Fan operation halts without alarm, in absence of fan-enable signal.

Control Logic Circuits

In general, digital electronic logic refers to circuitry in which inputs and outputs are constrained to either "high" or "low" levels. For convenience in logic notation, the levels are often designated as "true" or "1" and "false" or "0." Logic circuits can be combined to perform true-false decisions based on the presence or absence of highs and lows on various inputs. Memory elements permit the history of previous input and output levels to be taken into account.

The two states are commonly defined in terms of voltage levels; the former being at the power supply voltage, the latter at ground potential. These levels correspond conveniently with "on" and "off" states in inputs and outputs. As such, digital logic is ideal for direct control application involving simple on-off input sensors and output loads. Logic in
Figure 25. Flow diagram, fan alarm
ENABLE FAN

ZERO COUNTER

ENABLE CLOCK

5-SEC. ELAPSED ?

FAN UP TO SPEED ?

STILL OPERATING ?

STILL ENABLED ?

SET ALARM

STOP
which the active state is taken as true, or high, is referred to as positive logic.

A digital logic family consists of a group of compatible integrated circuits that can be combined to perform desired logic functions. In recent years, TTL (transistor-transistor logic) has been the "standard" logic family for most logic applications. More recently, logic families with certain improvements over TTL have been developed. Among them, the CMOS (complementary metal-oxide semiconductor) logic family offers particular advantages for control applications (Kalin, 1972; Olson and Borsa, 1973a, 1973b; Wallace, 1973). Three of these advantages are:

1. Much lower power consumption. Static dissipation is typically 10 nW per gate (Calebotta, 1975). Battery operation is practical.
2. Higher noise immunity, typically 45 percent of the supply voltage (Eaton, 1970). Operation is less susceptible to problems arising from electrical noise generated by motors, relay contacts, etc.
3. Wider power supply range, typically 3 to 15 volts (Pujol, 1971). Unregulated, lightly-filtered power supplies are adequate.

A disadvantage of CMOS devices is their susceptibility to damage from high static electrical charges (Stephenson, 1975). Manufacturers have reduced the problem through design improvements. Care in handling during fabrication is required (Dansky and Funk, 1974).

The CMOS family was chosen for the control logic in this investigation. Circuit development and testing were carried out using 54L/74L series TTL components because of the author's familiarity with this logic family. Final designs were specified from the 54C/74C series of CMOS logic which is equivalent in function and pin assignments (Redfern, 1975b).
Development of the logic circuitry followed suggested design procedures (Malmstadt and Enke, 1969; Peart, 1972; Soderholm and Charity, 1972; Lancaster, 1974; Larsen et al., 1974; Rony et al., 1974; Johnson, 1975). Specifications and operating characteristics of individual components were obtained from manufacturers' literature (RCA, 1972; Fairchild Semiconductor, 1973; National Semiconductor, 1975; RCA, 1975; Motorola, 1976; National Semiconductor, 1976; Signetics, 1976). Individual logic modules were breadboarded to verify operation.

Initialization logic

A tabulation of the functions comprising the initialization matrix is given in Table 13. The table shows that, for each of the 24 possible combinations of initialization settings, a unique combination of nine output functions is required. Two separate logic circuits were developed to generate the needed outputs. The first design was based on combinations of conventional logic gates. The second, incorporating a programmable read-only memory (PROM), utilized stored-logic techniques.

For the combinational logic design, Karnaugh mapping (Texas Instruments, 1971) was used to simplify and minimize the truth table functions of Table 13. A solution using conventional logic gates is shown in Figure 26. Output functions for the preset inputs of the "weeks delay" counter in the fan control logic, assume a clock frequency of 0.5 cycles per day. Accordingly, the desired weeks of delay are programmed by presetting the counter for half the apparent number of required days.

 Auxiliary logic is required to interface the counter preset outputs of the initialization logic with the preset inputs to the weeks delay counter.
Figure 26. Schematic diagram of initialization logic using individual logic gates
IC 1, 9: 74C04, Hex Inverter
IC 2, 6, 7: 74C00, Quad 2-Input NAND Gate
IC 3: 74C02, Quad 2-Input NOR Gate
IC 4: 74C86, Quad 2-Input EXCLUSIVE-OR Gate
IC 5, 8: 74C08, Quad 2-Input AND Gate
R: 100K
Each output signal is conditioned to generate the appropriate 3-bit, binary-coded presets for the 4-bit counter. The fourth bit, having a fixed value of \(2^0 = 1\), is connected directly to \(V_{cc}\).

The interface is achieved conveniently by means of three-state logic gates (Figure 27). This logic offers a third output state that is, in effect, an open circuit (Lancaster, 1974). With the enable control activated, the output follows the logic level of the input. In the third state, the output "floats," ignoring inputs and assuming the level of any active connection.

A PROM integrated circuit was used in the second initialization logic design to eliminate most of the individual logic gates of the first approach. The PROM is a semiconductor memory device that is programmable by the user (Frankenberg, 1975). Individual memory elements are composed of fusible links which may be "blown" selectively to store the desired digital program.

The specified PROM contains 256 bits organized into 32, 8-bit words (Signetics, 1976). Each word may be accessed by means of binary-coded address lines. The word stored in any addressed location appears on the output lines.

Address decoding was required to interface the initialization selector switches with the address lines of the PROM. Three-state gates were combined with inverters to generate a unique 5-bit, binary-coded address for each of the 24 possible combinations (Figure 28). Buffered inverters were specified to perform the required voltage translation (Jorgensen and Redfern, 1975). Initialization combinations and assigned PROM addresses are given in Table 14.
Figure 27. Schematic diagram of logic interface between initialization logic and presets of weeks delay counter
IC 1-3: 80C97, Three-State Hex Buffer
Figure 28. Schematic diagram of initialization logic, using programmable read-only memory (PROM)
IC 1: 74C901, Hex Inverting Buffer
IC 2: 80C97, Three-State Hex Buffer
IC 3: 80C97, Three-State Hex Buffer
IC 4: N8223, Bipolar PROM (32X8)
R: 100K, all

Q0: Counter inhibit
Q1: Counter preset, D
Q2: Counter preset, C
Q3: Counter preset, B
Q4: Spring dry
Q5: Fall dry
Q6: Unsuccessful
Q7: Heater enable
Table 14. Initialization matrix functions and assigned PROM\(^a\) addresses

<table>
<thead>
<tr>
<th>Harvest date</th>
<th>Moisture (%)</th>
<th>Airflow (cfm/bu)</th>
<th>PROM address</th>
<th>Decimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 15</td>
<td>22 24 26</td>
<td>1.5 2.0 2.5 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov. 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0(^b) 1(^c)</td>
<td>0 1 1 1</td>
<td>0 1 1 1</td>
<td>0 0 1 1 1 1</td>
<td>7</td>
</tr>
<tr>
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\(^a\)PROM = programmable read-only memory.
\(^b\)0 = false, off.
\(^c\)1 = true, on.
Table 15 shows PROM addresses with desired output functions. Programming the PROM according to this truth table provides the required combinations of output control functions. Direct binary coding of counter presets reduces the required number of output functions per combination from 9 to 8. A "don't care" condition exists for each memory location not addressed.

In terms of design convenience and flexibility, the PROM offers distinct advantages over individual logic gates. A drawback in this application is the 5-volt operating voltage of the PROM. A revision of the suggested power supply would be necessary to meet the dual-voltage requirement (Blandford and Bishop, 1974; Longacre, 1976).

System clock

The proposed control scheme specifies several time-dependent control functions. Both real-time and relative-time relationships are utilized. A system "clock" was designed to provide the digital timing signals required by the clocked logic functions.

Required system clock frequencies were as follows:

1 Hz - fan alarm logic
1 cycle per hour - fan control logic
1 cycle per day (real time) - aeration logic, aeration exit logic
0.5 cycle per day - fan control logic

For convenience in generating the necessary periodic signals, an integrated circuit clock "chip" was chosen as the basic oscillator (Figure 29). The time base for the chip was derived from the 60 Hz line frequency. An on-board backup oscillator was included to maintain the time base during standby battery operation.
Table 15. PROM addresses with corresponding output functions

<table>
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<tr>
<th>PROM address</th>
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<th>PROM output</th>
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<td>Q₃</td>
<td>Q₄</td>
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\[ a \] = counter preset, 2³.
\[ b \] = counter preset, 2².
\[ c \] = counter preset, 2¹.
\[ d \] = "don't care" condition.
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Figure 29. Schematic diagram of system clock and power supply
IC 1: 7001, Clock Chip
IC 2-5: 74C90, 4-Bit Decade Counter
IC 3: 74C76, Dual Bistable Multivibrator

Diodes: 1N4001

12VAC
115VAC

IC 1

4-Digit, 7-Segment LED Display

Segment Drive
Digit Drive

15K
15K

0.01μF 22K

500μF 12V

IC 2 (×6)

IC 3 (×6)

IC 4 (×10)

IC 5 (×10)
Output frequencies of 1 Hz and 1 cycle per day (real time) were available directly. The former digital signal was divided by 3600 to obtain a frequency of 1 cycle per hour, as shown in Figure 29. A frequency of 0.5 cycle per day was obtained by dividing the latter digital signal by 2.

Power supply requirements of the clock chip and CMOS logic are compatible and nonrigorous (Pujol, 1971). A suggested power supply with automatically activated battery standby is included in Figure 29.

Clocked logic circuits

The proposed control scheme assumes the use of simple "on-off" thermostats and humidistats as input sensors. Movement of the electrical contacts is accompanied by "bounce" as the switch changes state. False signals are generated until the contacts come to rest. Such signals must be "de-bounced" for reliable operation with clocked-logic circuits.

Digital "de-bouncers," suitable for use with single-pole, single-throw switches, were specified for all thermostat and humidistat inputs (Figure 30). A delay in state change of approximately 2 seconds is introduced to permit switch contacts to settle (Motorola, 1976). A logical 1 signal appears at the output when the input switch is open.

A synchronous 4-bit binary counter was chosen for counter functions (Heuner et al., 1972). Count values between 1 and 16 are selected by applying appropriate signal levels to the binary-coded preset inputs. Counting may proceed either up to, or down from, the preset number. Synchronous operation minimizes problems arising from propagation "glitches."
Figure 30. Schematic diagram of fan control logic; typical de-bounce circuit, 3-hour delay counter, and weeks delay counter
START/STOP
DISABLE GRAIN TEMP. ≥ 45°F
GRAIN TEMP. ≥ 45°F
AERATE
COUNTER PRESETS
COUNTER INHIBIT
0.5 c/day
RESET

AMBIENT RH ≥ 90%
1 c/hr
RESET

IC 1: MC14490, Hex Contact Bounce Eliminator
IC 2-3: 74C193, Synchronous 4-Bit Binary Counter
IC 4-5: 74C04, Hex Inverter
IC 6-7: 74C08, Quad 2-Input AND Gate
IC 8: 74C02, Quad 2-Input NOR Gate
IC 9: 74C221, Dual Monostable Multiv.

Oscil1ator
Count D C B A Down WEEKS DELAY IC 2
IC 6
Load CLR Borrow
IC 7

IC 7

IC 9
Count D C B A Down 3-HOUR DELAY IC 3
Load CLR Borrow
IC 8

3µF

0.1µF 100K

1 µF

HEATER/FAN INTERLOCK
TO FAN ALARM
TO FAN RELAY
Reset signals were obtained from monostable multivibrators wired for a delay of approximately 10 ms (Redfern, 1975a). Bistable multivibrators were used as memory elements and for divide-by-two functions.

The clocked logic circuits developed in this investigation are shown in Figures 30-34. Functional operation follows the flow diagrams presented previously (Figures 20-25).
Figure 31. Schematic diagram of logic for (a) heater control and (b) exit from drying mode
HEATER/FAN INTERLOCK

AMBIENT RH ≤ 60%

HEATER ENABLE

HEATER DISABLE

TO SOLID STATE HEATER RELAY

TO INDICATOR LAMP DRIVER

(a)

SELECT DRY AERATION CYCLE

SELECT WET AERATION CYCLE

GRAIN ≤ 35°F

(b)

IC 1: 74C04, Hex Inverter
IC 2: 74C00, Quad 2-Input NAND Gate
IC 3: 74C02, Quad 2-Input NOR Gate
Figure 32. Schematic diagram of aeration mode logic
Figure 32, continued
IC 1, 12, 19: 74C04, Hex Inverter
IC 2, 3, 9, 10, 11, 20: 74C08, Quad 2-Input AND Gate
IC 4, 14: 74C02, Quad 2-Input NOR Gate
IC 5, 15-17: 74C76, Dual Bistable Multivibrator
IC 6, 18: 74C221, Dual Monostable Multivibrator
IC 7, 8, 13, 21: 74C193, Synchronous 4-Bit Binary Counter

Figure 32, continued
Figure 33. Schematic diagram of logic for exit from aeration mode
IC 1: 74C04, Hex Inverter
IC 2: 74C00, Quad 2-Input NAND Gate
IC 3-4: 74C76, Dual Bistable Multivibrator
IC 5: 74C221, Dual Monostable Multivibrator
IC 6: 74C02, Quad 2-Input NOR Gate
IC 7: 74C86, Quad 2-Input EXCLUSIVE-OR Gate
Figure 34. Schematic diagram of fan alarm logic
1 Hz CLOCK

SAIL SWITCH

FAN ENABLE

RESET

IC 1: 74C08, Quad 2-Input AND Gate
IC 2: 74C193, Synchronous 4-Bit Binary Counter
IC 3: 74C02, Quad 2-Input NOR Gate
IC 4: 74C221, Dual Monostable Multivibrator
IC 5: 74C76, Dual Bistable Multivibrator
IC 6: 74C04, Hex Inverter
DISCUSSION AND CONCLUSIONS

Discussion

Initialization matrix

The initialization matrix permits the operator to "program" the control system for an anticipated combination of harvest conditions. Humidistatic fan control and heater operation are set automatically. Visual feedback from the control system signals whether the predicted probability of drying success is greater than 90 percent and whether completion of drying can be expected in the fall or spring.

Unsuccessful combinations inhibit system operation. Operator interaction is required. With an unsuccessful combination of harvest date, moisture content, and airflow rate, for example, the operator may choose a higher "successful" airflow setting and reduce the planned depth of fill to the corresponding level. By examining settings prior to harvest, the operator may plan, in advance, to approximate a successful combination.

Since the initialization matrix is based on long-term simulation of actual drying seasons, its validity rests heavily on the accuracy of the simulation model. Further, direct application is limited to a geographical radius that is representative of the weather data employed in the simulation.

The number of harvest settings included in the proposed matrix was limited by demands on computer time. Additional combinations would offer more extensive applicability. A matrix based on success probabilities that are less demanding than the 90 percent level would permit accepting greater risk to obtain increased flexibility and economy of operation.
Changes in the matrix would require a redesign of the initialization logic. In the case of the memory-based logic, this alteration could be accomplished conveniently by programming another PROM integrated circuit. Adapting the control system for other geographical locations would simply require the installation of an appropriately programmed, plug-in PROM.

**Fan and heater control**

Energy savings were predicted from simulated control of the fan and heater. Analysis of 10 years of weather data showed that the control system would halt fan operation to minimize rewetting an average of 9 percent of the drying season hours. If enabled, heater operation would also be interrupted. A corresponding average reduction in consumption of electrical energy would result.

Long-term weather data indicate that the control system would halt heater operation for low-humidity conditions an average of over 30 percent of the drying season hours. Average consumption of electrical energy for heater operation would be reduced accordingly.

The proposed fan and heater control modes are humidistat-actuated. Past experience with common humidistats indicates that accuracy degrades rapidly in a dusty operating environment. Periodic cleaning and recalibration are required (Noyes, 1967). Humidistats with better accuracy and reliability are available at higher cost.

**Aeration control**

Simulation of aeration-mode operation over 10 seasons predicted acceptable performance by both the dry-grain and wet-grain aeration cycles. Average equilibrium moisture contents for the hours of aeration during each
season met the desired level. Ample hours of aeration were indicated. The automatic exit from the aeration mode was shown to function satisfactorily. For conditions differing from those of this investigation, alternative aeration schemes may be desired. Limits on ambient sensors are easily adjusted. Simple lead changes on counter presets in the aeration logic permit wide flexibility in duration of aeration and wait periods.

**Solar low-temperature drying**

Interest in solar grain drying has increased in recent months. Fluctuations in price and availability of conventional fuels has spurred the search for alternative energy sources. Solar supplementation has been shown to be compatible with low-temperature drying methods (Bauman et al., 1975; Kranzler et al., 1975; Meyer et al., 1975; Morey and Nelson, 1975; Peterson and Hellickson, 1975). The control system developed in this investigation is easily adapted for use with solar low-temperature drying. Two possible control modes will be described.

First, a solar system designed to maintain a minimum temperature rise may be desired. Controlled heater operation is needed to augment the solar collector output during night hours and overcast days. The required control signal for temperature rise can be obtained from a simple differential thermostat sensing ambient and plenum air temperatures. Substitution of this sensor for the humidistat input to the heater control logic (Figure 31) yields the desired automatic heater control function.

A second appropriate management strategy may be to retain the heater as a backup energy source for prolonged periods of inadequate solar collector output. For this mode of operation, the differential thermostat would
be connected to reset a "day counter" whenever a specified temperature rise is exceeded. Should the counter fail to be reset within a preset number of days, the heater would activate automatically until the next reset signal. Counter circuitry similar in operation to the fan alarm logic (Figure 34) would be substituted for the humidistat input to the heater control logic (Figure 31). The required 1 cycle-per-day signal to the counter is available from the system clock.

In both cases, modification of the initialization matrix would be desirable to reflect the predicted average output of the solar collector. All other system control modes, including exits, would be directly compatible with solar-supplemented low-temperature drying.

Microcomputer control

As indicated previously, a major deterrent to the development of a closed-loop control system for low-temperature drying is the lack of reliable feedback information on grain moisture levels. Thus, a fully automatic control system awaits the development of suitable sensors for moisture content in bulk grains. Recent advances in microprocessor and microcomputer technology, however, show promise of circumventing this problem.

The microcomputer makes practical the direct application of computer methods to dedicated process control under field conditions (Larsen et al., 1975; Osborne and Associates, 1975). Previous work has demonstrated the feasibility of full-scale computer control of grain drying (Holtman and Zachariah, 1969). Optimal control of a crossflow dryer was achieved through the use of a resident model of the drying process (Holtman, 1967).
A similar approach to the control of low-temperature drying would appear to have merit. Ambient temperature and relative humidity would be monitored by the microcomputer, as a measure of process input conditions. A model of the low-temperature drying process stored in memory would enable the microcomputer to calculate the grain moisture content at assigned locations in the bin. Control decisions could then be based on predicted moisture levels and on predicted (or measured) grain temperatures. Fully automatic operation, including adaptive control and shutdown for completion of drying, would result.

Conclusions

A control scheme and digital electronic control system for low-temperature drying of shelled corn were developed in this investigation. Performance predicted from analysis of long-term weather data and from simulated operation of control modes shows that the control system may be expected to:

1. reduce the risk of unsuccessful drying due to spoilage by identifying combinations of starting conditions with a high probability of success,

2. increase efficiency of drying by reducing fan and heater consumption of electrical energy, and

3. reduce management requirements, through automatic control of the fan and heater during drying and of fan operation during aeration.
SUGGESTIONS FOR FUTURE STUDY

Results of this investigation suggest the following areas for future study:

1. Construct a prototype of the proposed control system and evaluate performance under field conditions.

2. Expand the range of drying simulations to include a more extensive selection of harvest dates and harvest moisture contents.

3. Investigate additional levels of probability of drying success and incorporate results in initialization matrix to permit operation according to selected levels of risk.

4. Modify computer model to permit direct simulation of the performance of comprehensive control schemes.

5. Investigate the feasibility of microcomputer control of low-temperature drying based on a resident model of the drying process.


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APPENDIX A: DEFINITION OF PSYCHOMETRIC TERMS

1. **Vapor pressure** - partial pressure exerted by the water vapor molecules in moist air.

2. **Relative humidity** - ratio of the vapor pressure of moist air to the vapor pressure in saturated air at the same temperature and atmospheric pressure.

3. **Humidity ratio** - weight of the water vapor contained in the moist air per unit weight of dry air.

4. **Dry-bulb temperature** - temperature of moist air as indicated by an ordinary thermometer.

5. **Wet-bulb temperature** - temperature of moist air as indicated by a thermometer having its bulb covered with a wet wick under forced aeration.

6. **Dew-point temperature** - temperature at which condensation occurs when the moist air is cooled at constant humidity ratio and atmospheric pressure.

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<sup>1</sup> Based on Brooker et al. (1974).
APPENDIX B:
THOMPSON LOW-TEMPERATURE DRYING/AERATION MODEL

The Thompson low-temperature drying model assumes the deep bed of grain to consist of a series of thin layers stacked normal to the upward flow of air in the bin. Official weather data are used to specify the state point of the input air to the bottom layer. As each layer is aerated for a short time interval, Δt, its exhaust air becomes the input air to the layer above. When all the layers have been scanned, the procedure is repeated.

Average changes in the exhaust air and the grain during the specified time interval are simulated for each thin layer of grain. The model then predicts grain temperature, moisture content, and dry matter decomposition resulting from (a) respiration within the grain, (b) heat transfer through the bin wall, and (c) conditioning of the grain through continuous low-temperature drying/aeration. The simulation procedure is charted in Figure 35. A description of the model, based on Thompson (1972), is given below.

Heat of Respiration

The respiration process in stored grains is generally regarded as a conversion of dry matter to carbon dioxide and water (Milner and Geddes, 1954). Microorganisms on and within the kernels, as well as the grain itself, are involved (Hummel et al., 1954). Typically, hexose carbohydrates are oxidized according to the exothermic reaction (Pomeranz, 1974):

\[ C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + 677.2 \text{ Cal.} \]
Figure 35. Flow diagram, simulation program
START

READ INITIAL PARAMETERS

READ AMBIENT AIR CONDITIONS AND INCREMENT TIME PERIOD, $\Delta T$

PREDICT CHANGES IN GRAIN TEMP. DUE TO HEAT OF RESPIRATION AND HEAT TRANSFER

PREDICT DRY MATTER DECOMPOSITION

SIMULATE AERATION/DRYING PROCESS

TIME TO PRINT ?

NO

YES

PRINT RESULTS

TIME TO STOP ?

NO

YES

STOP
If it is assumed that the energy produced from this decomposition is equivalent to that resulting from the complete combustion of dry matter lost, the heat of respiration can be predicted for various corn moistures and temperatures.

In the simulation model, the rate of increase of grain temperature attributable to respiration is computed by multiplying the percentage of dry matter lost during the storage interval (Δt) by the associated heat of respiration and dividing this product by the sensible heat required to change the temperature of the grain (Thompson et al., 1971). Similarly, the moisture content of the grain is increased by an amount proportional to the percent dry matter loss.

**Heat Transfer**

Heat flow through the bin wall for each layer of grain and each time interval (Δt) is calculated from the formula:

$$Q = AU(G_0 - T_o)$$

Where:

- $Q = \text{heat flow through the wall, Btu per hr}$
- $A = \text{wall surface area per layer of grain, sq ft}$
- $U = \text{overall heat conductance of the wall, Btu per sq ft-hr-o°F}$
- $G_0 = \text{initial grain temperature, o°F}$
- $T_o = \text{initial air temperature, o°F}$

The rate of change of grain temperature caused by heat transfer for each layer is computed by dividing the heat flow by the sensible heat required to change the temperature of the grain by 1 o°F. Conductive heat
transfer between kernels is assumed to be negligible compared with the conveective transfer within the bed.

**Dry Matter Decomposition**

The simulation of dry matter decomposition is based on work by Steele et al. (1969) in which carbon dioxide production from shelled corn held under various laboratory storage conditions was related to dry matter decomposition. Families of curves were developed to permit the calculation of allowable storage times as a function of grain temperature, moisture content, and mechanical damage.

Thompson uses mathematical representations of these curves to model dry matter decomposition of shelled corn under dynamically varying storage conditions. The equations employed (Thompson, 1972) included the correction for low-temperature storage conditions as reported by Saul (1970).

Predicted dry matter decomposition is used in the model to indicate the condition of the corn during the simulated drying-aeration period and as an index of comparison for different storage conditions.

**Drying-Aeration Process**

The low-temperature drying model developed by Bloome and Shove (1971) approximates equilibrium conditions between the air and the grain by following a separate algorithm for each of the four possible process combinations of heating or cooling and drying or wetting. Thompson uses a simplified version of this model to simulate shelled-corn aeration. Like Bloome's model, it is restricted to use at near-equilibrium storage conditions such as those associated with low-temperature, low-airflow drying/aeration.
Three basic assumptions underlie the revised model:

1. True equilibrium is obtained between the air and the grain for the drying time interval (Δt).

2. Heat and mass transfer between the air and the grain is adiabatic.

3. No hysteresis exists between the sorption and desorption isotherm relating equilibrium moisture content of the grain to equilibrium relative humidity of the air.

Calculation of grain-air equilibrium conditions involves the following:

1. A heat balance between the air and grain.

\[
0.24T_o + H_o (1060.8 + 0.45T_o) + CG_o + (H_f - H_o) (G_o - 32) = 0.24T_f + H_f (1060.8 + 0.45T_f) + CT_f
\]

Where:

- \( T_o \) = initial grain temperature, °F
- \( H_o \) = initial absolute humidity of the air, lb H₂O per lb dry air
- \( C \) = specific heat of corn, Btu per lb air - °F
- \( G_o \) = initial grain temperature, °F
- \( H_f \) = final absolute humidity of the air, lb H₂O per lb dry air
- \( T_f \) = final grain temperature, °F

2. A mass balance between the air and the grain.

\[
H_f - H_o = \frac{(M_o - M_f) R}{100}
\]

Where:

- \( M_o \) = initial moisture content, percent dry basis
- \( M_f \) = final moisture content, percent dry basis
- \( R \) = dry matter-to-air ratio, lb dry matter per lb air
3. Equality between the equilibrium relative humidity (ERH) of the air within the grain layer and the relative humidity (RH) of the exit air at the end of the simulation interval.

The equilibrium conditions thus defined result in three equations and three unknowns. Computer search techniques (Thompson and Peart, 1968) are used to obtain an iterative solution as follows:

1. $H_f$ is estimated.
2. $T_f$ is calculated from the heat balance equation.
3. $M_f$ is calculated from the mass balance equation.
4. ERH is calculated from $T_f$ and $M_f$. For corn (Thompson et al., 1968),
   \[
   \text{ERH} = 1 - \exp \left[ -3.82 \times 10^{-5} (T_f + 50)M_f^2 \right]
   \]
5. RH is calculated from $T_f$ and $H_f$ (Brooker, 1967).
6. $H_f$ is estimated again using the function, \( \text{ERH} - \text{RH} \).

This sequence is repeated until \( \text{ERH} - \text{RH} \) is sufficiently close to zero. Less than six trials are normally required for convergence to the desired equilibrium point.

Initialization Parameters

Major inputs to the model consist of the weather data for the drying season to be simulated and the harvest conditions at the onset of drying. A degree of management flexibility is also provided. The model accepts the following initialization parameters:

1. Weather data
   (a) starting date of data and number of days in data set
   (b) daily dry bulb and dew point temperatures, 3-hour intervals
2. Initial conditions
   (a) start of drying, month and day
   (b) grain moisture content, percent (wet basis)
   (c) airflow rate, cfm per bu

3. Management strategy
   (a) set point for humidistat control of heater, percent relative humidity
   (b) amount of heat to be added (temperature rise), °F
   (c) number of weeks at a given management strategy
   (d) airflow rate for each week, cfm per bu
   (e) number of hours per day of fan operation
   (f) time of day at which fan is started, 24-hr clock
   (g) number of days per week at a given management strategy

Output Data

Major outputs of the program are listed below.

1. Minimum required airflow.

   The program automatically calculates the minimum airflow rate required for drying "success" as defined by:
   (a) a maximum final moisture content of 15 percent
   (b) a maximum final dry-matter decomposition of 0.5 percent

   The program considers both short-term (fall) and long-term (winter or spring) completion of drying in arriving at a minimum airflow. Continuous operation of the fan and supplemental heat is assumed.

   Specific output data include:
   (a) date of completion, month and day
2. Weekly summary of drying progress.

The following weekly output-data summaries are printed:

(a) moisture content for each of 12 bin layers, percent
(b) grain temperature for each of 12 bin layers, °F
(c) dry-matter decomposition for each of 12 bin layers, percent
(d) maximum and minimum layer moisture content, percent
(e) maximum and minimum layer grain temperature, °F
(f) maximum and minimum layer dry-matter decomposition, percent
(g) average moisture content, percent
(h) average grain temperature, °F
(i) average dry-matter decomposition, percent

Termination of a simulation run occurs when one of the following conditions is encountered:

1. No weather-data input is available.
2. Wettest layer is at 15 percent moisture content or below.
3. Dry-matter decomposition is at 1.5 percent or greater.
4. Limit of weekly management regime is reached.
Table 16. Simulation results, minimum required airflow for successful drying, ascending order

<table>
<thead>
<tr>
<th>Harvest date</th>
<th>Harvest moisture rise (°F, total)</th>
<th>Minimum airflow, weeks to dry, and drying season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct. 15</td>
<td>22</td>
<td>0.36\textsuperscript{a} b c 0.41 29 67 0.52 30 66 0.53 33 60 0.78 31 68</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>24</td>
<td>0.69 25 69 1.02 30 61 1.27 26 65 1.32 08 64 1.64 06 63</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>24</td>
<td>0.79 23 69 0.79 26 67 1.00 26 66 1.01 11 60 1.17 10 62</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>24</td>
<td>1.41 11 68 1.72 08 64 2.06 07 65 2.18 28 61 4.42 04 63</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>26</td>
<td>0.79 23 69 0.84 24 67 0.89 10 66 1.01 10 60 1.24 09 62</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>26</td>
<td>1.40 10 68 1.67 06 64 1.85 27 61 2.25 05 65 4.18 04 63</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>26</td>
<td>1.40 23 67 1.50 09 69 1.68 08 60 2.34 06 62</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>26</td>
<td>1.40 23 67 1.43 24 66 1.50 09 69 1.68 08 60 2.34 06 62</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>26</td>
<td>2.69 07 64 2.77 10 68 3.35 27 61 4.89 04 65 6.96 04 63</td>
</tr>
<tr>
<td>Oct. 15</td>
<td>26</td>
<td>2.37 04 64 2.45 04 61 2.46 04 68 4.05 02 65 4.90 03 63</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Minimum airflow (cfm/bu).
\textsuperscript{b}Weeks to dry (no.).
\textsuperscript{c}Drying season (yr).
Table 16. (continued)

<table>
<thead>
<tr>
<th>Harvest date</th>
<th>Temperature rise (°F, % w.b. total)</th>
<th>Minimum airflow, weeks to dry, and drying season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov. 1 22</td>
<td>0.40 28 69</td>
<td>0.45 08 67</td>
</tr>
<tr>
<td></td>
<td>0.61 08 66</td>
<td>0.63 27 68</td>
</tr>
<tr>
<td></td>
<td>0.72 27 61</td>
<td>0.92 27 63</td>
</tr>
<tr>
<td></td>
<td>0.59 27 62</td>
<td>0.70 27 65</td>
</tr>
<tr>
<td>Nov. 1 24</td>
<td>0.54 27 69</td>
<td>0.67 26 67</td>
</tr>
<tr>
<td></td>
<td>0.89 26 66</td>
<td>1.04 30 61</td>
</tr>
<tr>
<td></td>
<td>0.69 31 68</td>
<td>1.08 27 65</td>
</tr>
<tr>
<td></td>
<td>0.71 31 60</td>
<td>0.75 28 63</td>
</tr>
<tr>
<td></td>
<td>0.75 28 63</td>
<td>3.51 07 64</td>
</tr>
<tr>
<td>Nov. 1 24</td>
<td>0.56 26 69</td>
<td>0.63 29 68</td>
</tr>
<tr>
<td></td>
<td>0.86 21 66</td>
<td>0.88 29 61</td>
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<tr>
<td></td>
<td>0.65 24 60</td>
<td>1.10 24 65</td>
</tr>
<tr>
<td></td>
<td>0.72 25 67</td>
<td>0.78 21 63</td>
</tr>
<tr>
<td></td>
<td>0.75 28 63</td>
<td>2.48 08 64</td>
</tr>
<tr>
<td>Nov. 1 26</td>
<td>0.93 17 69</td>
<td>1.17 25 68</td>
</tr>
<tr>
<td></td>
<td>1.84 20 66</td>
<td>1.86 22 62</td>
</tr>
<tr>
<td></td>
<td>1.21 20 67</td>
<td>2.13 22 65</td>
</tr>
<tr>
<td></td>
<td>1.50 25 60</td>
<td>2.24 24 61</td>
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<td></td>
<td>1.50 25 60</td>
<td>1.68 20 63</td>
</tr>
<tr>
<td></td>
<td>1.60 20 63</td>
<td>5.30 03 64</td>
</tr>
<tr>
<td>Nov. 1 26</td>
<td>0.93 17 69</td>
<td>0.94 23 68</td>
</tr>
<tr>
<td></td>
<td>1.65 07 63</td>
<td>1.69 18 66</td>
</tr>
<tr>
<td></td>
<td>1.18 18 67</td>
<td>1.78 06 65</td>
</tr>
<tr>
<td></td>
<td>1.29 08 60</td>
<td>1.83 23 61</td>
</tr>
<tr>
<td></td>
<td>1.60 22 62</td>
<td>3.66 03 64</td>
</tr>
</tbody>
</table>

Successful drying: final moisture content ≤ 15% w.b.
final dry-matter decomposition ≤ 0.5%
1960-1969 weather data; Des Moines, Iowa
Data from Thompson (1975) included