United States
Department of
Agriculture

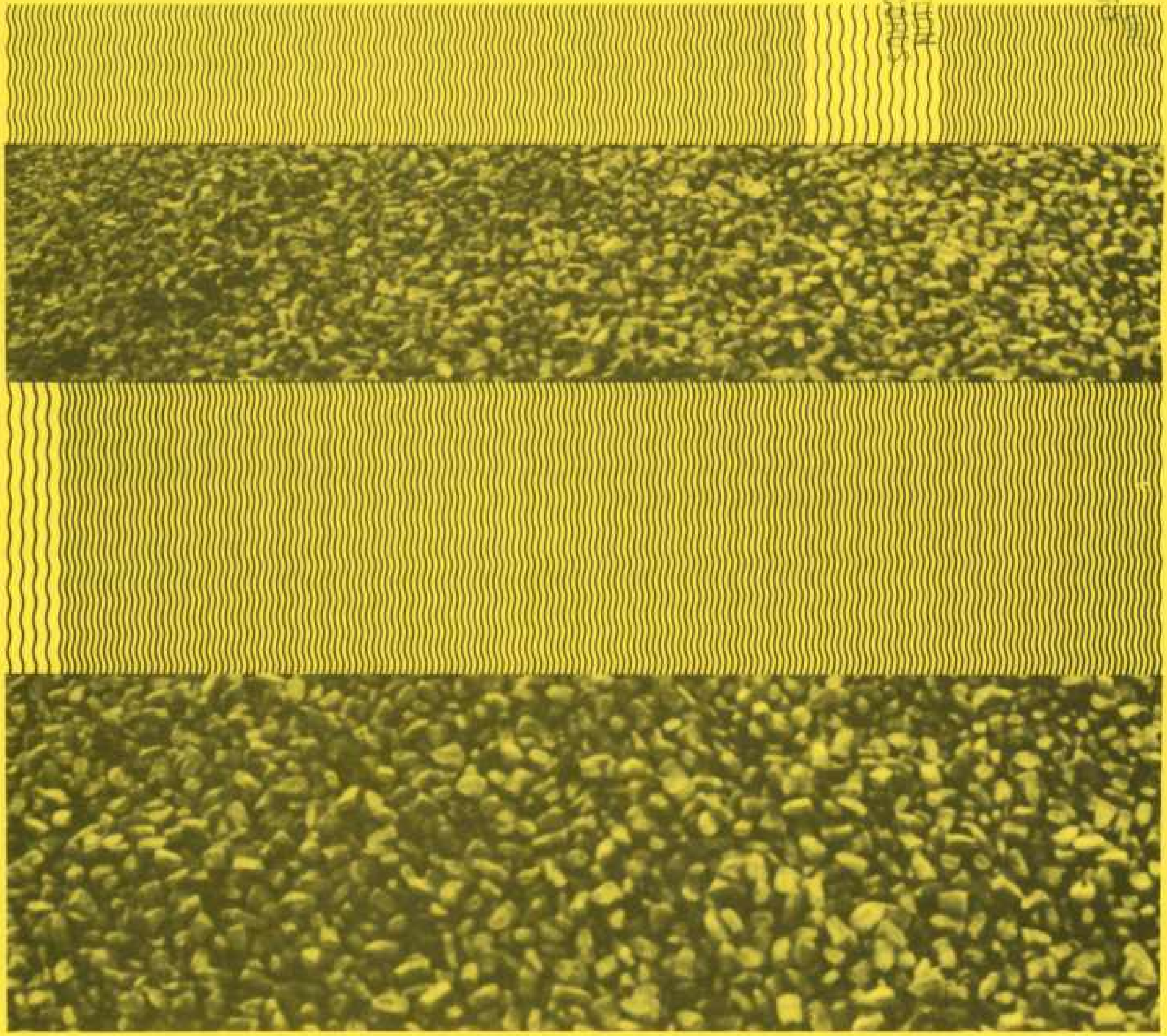
Economics and
Statistics
Service

Technical
Bulletin
Number 1654

Solar-Supplemented, Natural Air Drying of Shelled Corn

The Economic Limitations

Walter G. Heid, Jr.
David F. Aldis



SOLAR-SUPPLEMENTED, NATURAL AIR DRYING OF SHELLED CORN: THE ECONOMIC LIMITATIONS, by Walter G. Heid, Jr., and David F. Aldis; National Economics Division; Economics and Statistics Service; U.S. Department of Agriculture. Technical Bulletin No. 1654.

ABSTRACT

It is not economically feasible to supplement natural air drying of high-moisture shelled corn by adding heat (solar and otherwise). In some cases, that drying method speeds product deterioration. A simulation analysis of the west central Great Plains determined that benefits from adding solar heat to batch-in-bin and layer-in-bin grain drying methods failed to offset the solar heat installation costs and product deterioration losses. Findings also suggest that high-speed, high-temperature drying is necessary to avoid field losses and to ensure marketable corn of high quality.

Keywords: Solar, Natural air, Grain drying, Cost, Corn quality, Simulation.

NOTES

This study was conducted in cooperation with the Science and Education Administration, Agricultural Research, U.S. Grain Marketing Research Laboratory, Manhattan, Kans., and was partially funded by the U.S. Department of Energy. The report was reviewed and approved as Kansas Agricultural Experiment Station Contribution No. 81-398-B, Kansas State University, Manhattan, Kans.

Washington, D.C. 20250 June 1981

CONTENTS

ACKNOWLEDGMENTS

The authors thank the following persons who contributed to this study: Dean L. Bark, meteorologist, and Roger D. Jackson, research assistant, Weather Data Library, Physics Department, Kansas State University, Manhattan, Kansas; Gerald L. Kline, agricultural engineer, USDA, Iowa State University, Ames, Iowa; Gary R. Van Ee, agricultural engineer, formerly at Iowa State University now at Michigan State University, East Lansing, Michigan; and Harry H. Converse, agricultural engineer, USGMRL, Manhattan, Kansas.

SUMMARY

Adding solar heat or any other form of low-temperature supplemental heat to dry high-moisture shelled corn is not economically feasible compared with natural airflow drying. Solar-supplemented per-bushel costs far exceeded returns in the west central Great Plains, the corn-growing region with the highest average annual solar radiation.

The simulated analysis in this report used 20 years of weather and solar radiation data for Dodge City, Kans., an 8,000-bushel drying and storage system, and batch-in-bin and layer-in-bin drying methods. Price and cost data for the 1979/80 marketing year served as the economic base.

Supplemental solar heat had no effect on the batch-in-bin (single fill) strategy in good drying years, and failed to stem deterioration in poor drying years. High-moisture corn cannot be consistently preserved without using high-temperature dryers. Should fossil fuel for operating high-temperature grain dryers no longer be available, farmers insisting on fast harvest may choose to let their corn deteriorate a grade in poor drying years rather than invest in an uneconomical low-temperature dryer.

Layer-in-bin drying, although a method that could slow harvest, required no supplemental heat, even in years of high humidity after harvest. The addition of solar heat resulted in appreciable corn overdrying.

Results of a simulation model show that farmers can dry high-moisture corn more economically through natural airflow than by any form of supplemental heat, including solar energy. Farmers may allow more than 50 percent of their corn to deteriorate to grades No. 3 or 4 (low-quality corn), in poor drying years, and still lose less money than by installing a solar collector or some other supplemental heat source.

Solar-Supplemented, Natural Air Drying of Shelled Corn

The Economic Limitations

Walter G. Heid, Jr.*

David F. Aldis

INTRODUCTION

Farmers can dry high-moisture corn more economically through natural airflow than if they use any form of low-temperature supplemental heat, including solar energy, according to results of this simulation model.

Solar grain drying, being a slow, low-temperature method, is more closely related to natural air drying. It cannot be used to rapidly dry large volumes of high-moisture grain. Recognizing the limited role of solar grain drying and the costs associated with backup units assumed in previous studies, this study analyzes the use of solar energy as a supplement to natural air drying.

Two popular methods of drying, batch-in-bin and layer-in-bin, were simulated, using variables of initial corn moisture content, date of harvest, and weather. Results are analyzed by days required for corn moisture content to reach a safe storage level, accumulated deterioration, and costs of drying relative to market discounts for low-quality corn.

The use of solar collectors as a means of low-temperature grain drying is widely described in engineering literature. Previous studies have cast solar collectors in a primary drying role, assuming the use of backup units in years of poor drying weather (12, 18).1/ Research results are frequently reported in terms of energy savings relative to high-speed, high-temperature conventional grain drying.

Solar-supplemented drying of shelled corn may be economically feasible when employing a multiple-use system to dry lower moisture corn (9).

---

*Heid is an agricultural economist in the Economics and Statistics Service. Aldis is a research associate for the Science and Education Administration and assigned to the Chemical Engineering Department, Kansas State University. Both authors are stationed at the U.S. Grain Marketing Research Laboratory, Manhattan, Kans.

1/ Underlined numbers in parentheses cite references listed at the end of the report.

BACKGROUND AND VARIABLES

Several major factors such as delayed harvest, optional airflow needs (fan cost), the mixing of wet and dry corn, and the cash discounts for low-quality corn provide necessary input for computing costs and returns from grain drying and for making decisions on related strategies. Each of these factors affects situations in which a solar collector (supplemented heat) may enhance the drying of shelled corn, as well as situations when the use of a natural air system alone is most economical.

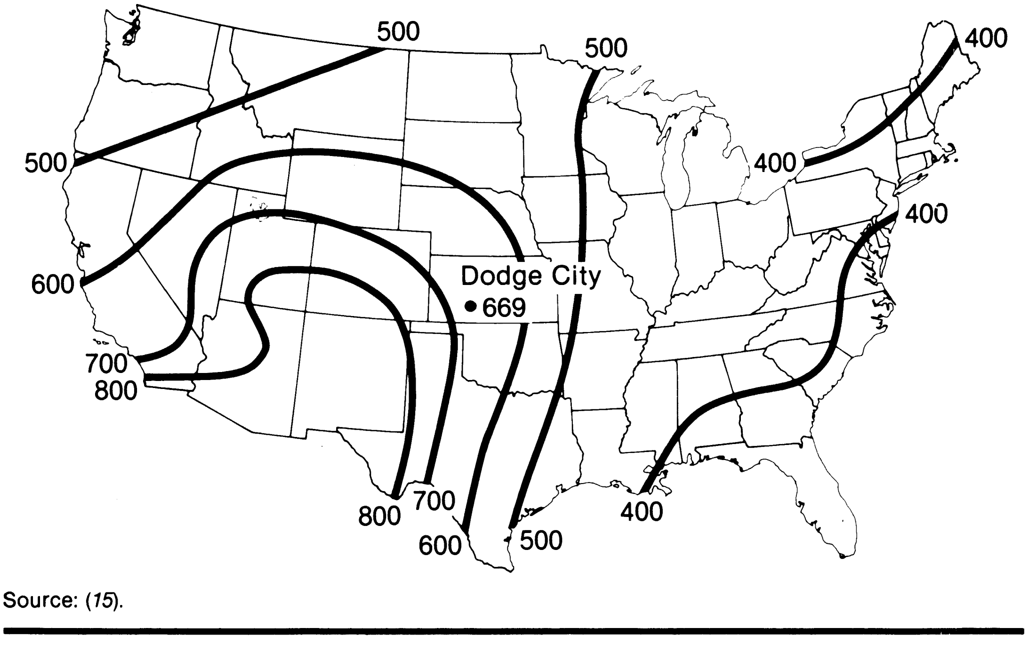
The west central Great Plains is generally considered to be an ideal location for harnessing solar energy. This region has the highest average annual insolation (incoming solar radiation) of any major corn-producing region. Climatological data for Dodge City, western Kansas, shows an average insolation of 669,000 British Thermal Units (Btu) per square foot annually (fig. 1). This compares with 400,000 to 500,000 Btu per square foot for most of the Corn Belt.

Weather Data

Twenty years (1955-74) of actual radiation and other weather data for Dodge City were used to predict performance of a natural air drying system with and without the input of a solar collection system. These data were obtained from solar and meteorological data tapes (SOLMET) purchased from the National

Figure 1

Average Annual Direct Normal Insolation (1,000 Btu/ft^2)



Source: (*15*).

Climatic Center, Asheville, N.C. Twenty years of data gave more reliable results than only 10 years of data would have because of the exceptional number of excellent crop years in the late sixties and early seventies. (Often a good crop year is associated with higher than average moisture conditions, signifying poor drying conditions.) As the study progressed, choice of the longer series proved important as probabilities of failure in some simulation runs were twice as high for one 10-year period as for the other.

Even though the region selected for this study is one of high insolation and is generally considered to be a low-humidity area, the 20 years of weather data revealed periods of extremely high humidity during the September-October harvest months. Average relative humidity for the September-simulated runs ranged from 30 to 71 percent. For the October runs, it ranged from 37 to 75 percent. In years of high average humidity, readings commonly ran over 85 percent for several consecutive days during the dry season. This, of course, suggests that drying conditions in the west central Great Plains may not be much different from parts of the Corn Belt in certain years.

Grain Deterioration and Weight Losses

High-moisture shelled corn deteriorates if it is not dried fast enough. However, it loses weight even if dried properly. Weight losses result in economic losses since producers are paid by the weight of their product. So producers must balance economic losses from deterioration with economic losses from lighter weight corn. Ideally, they need a corn drying system that achieves the optimum moisture content in the shortest time with the least deterioration.

Deterioration results from mold growth that causes both oxidation and the loss of dry matter. The dry-matter loss caused by mold growth can be estimated if the grain temperature, its moisture content, and the length of time the grain is maintained at the moisture content are known. If corn loses 0.5-percent dry matter by mold deterioration it will decline by at least one grade (12, 18). The allowable storage time for high-moisture shelled corn is shown in table 1. For more information concerning the loss of dry matter by mold deterioration, see (14).

When handled, shelled corn can also lose 0.5 percent of dry matter in the form of chaff and dust (5, 16). Such loss reduces the weight of the corn and affects its grade only if the fine material is not separated from the corn.

A bushel of 24-percent moisture corn contains 14.94 pounds of water, while a bushel of 15.5-percent moisture corn contains only 8.68 pounds. At 15.5-percent moisture, a bushel of corn

Table 1--Allowable storage time for high-moisture shelled corn

Corn storage temperature (degrees F)	Corn moisture content (percent)				
	18	20	22	24	26
	Days				
80	17	9	5	4	3
75	23	12	7	5	4
70	31	16	9	6	5
65	42	21	13	8	6
60	56	28	17	11	8
55	85	42	25	16	12
50	128	63	37	25	18
45	192	95	56	37	27
40	288	142	84	56	41
35	432	214	126	85	62
30	648	321	190	127	94

Source: (11).

(by volume) weighs 56 pounds. A bushel (by volume) of 24-percent moisture corn weighs 62.26 pounds (11). In effect, when moisture is removed, the weight of a bushel decreases. Since the price paid to farmers may be discounted for high moisture and low test weight, excess moisture reduction can mean lower profits.

For corn to be graded U.S. No. 1, it must have a minimum test weight of 56 pounds and a maximum moisture content of 14 percent. Requirements for No. 2 corn are a minimum of 54 pounds test weight and a maximum of 15.5-percent moisture content. For No. 3 corn, the requirements are 52 pounds for test weight and 17.5 percent for moisture. In each case, other factors are also considered (18).

Economic discounts given at the country elevator are based on U.S. No. 2 corn. Commonly, corn is discounted 1 to 1.5 cents a bushel for each 0.5-percent moisture above the standard 15.5 percent.

Values are quoted at major terminal markets for Nos. 2, 3, and 4 corn. The level of discount may vary from year to year depending on supply and demand. The amount of discount assumed in this study was based on the difference between No. 2 corn and lower grades on the Kansas City market in the fall of 1979:

Grade	Average price	Discount
	Dollars per bushel	Cents per bushel
No. 2	2.80	0
No. 3	2.70	10
No. 4	2.54	26

Discounts caused by high-moisture content can be averted by on-farm drying. If, however, the drying system fails to dry corn properly every year, costs associated with the occasional losses in quality (grain deterioration) must be prorated over all years. If 8,000 bushels of corn were graded No. 3 instead of No. 2, the loss would be $800, that is, 8,000 bushels x 10 cents. If, for example, a solar-supplemented, natural air drying system results in excessive dry-matter decomposition once every 10 years causing corn to be graded No. 3 instead of No. 2, the average annual loss would be 1 cent per bushel (table 2). If the system failed half of the time, the prorated cost would be 5 cents a bushel. On this basis, the probability of system failure is used to justify or reject the use of supplemental solar heat.

Table 2--Average annual economic loss due to corn quality deterioration

Grade reduction	Loss occurring during the indicated number of years in a decade				
	1	2	3	4	5
	Cents per bushel				
No. 2 to No. 3	0.010	0.020	0.030	0.040	0.050
No. 3 to No. 4	.016	.032	.048	.064	.080
No. 2 to No. 4	.026	.052	.078	.104	.130

Delayed Harvest

Harvests that begin any time from early September through October usually involve high-moisture corn and coincide with warmer, more humid drying weather than harvests that begin in November or later. Although the FALDRY model used in this study indicated that corn harvested September 15 could be dried from 25-percent moisture to 15.5-percent moisture in fewer days than corn harvested on October 15, deterioration was much greater in the earlier period.

Delayed harvest increases the feasibility of using natural air drying or low-temperature drying, first, because the corn generally contains less moisture and, second, because ambient air temperatures are cooler and humidity is lower.

Farmers may intentionally delay harvest by leaving corn in the field until after the time when harvest, technically, could commence, or by planting later maturing varieties. Normally, leaving harvest-ready corn in the field could result in severe economic losses.

Expected loss emanates from kernel moisture, cob moisture, and time. Field losses start mounting as soon as kernel moisture drops below 25 to 26 percent. If farmers wait until their corn dries to 20-percent moisture before harvesting, much of it will shatter and be left in the field (2). In contrast, corn kernels are too soft and fragile above 26- to 28-percent moisture content to harvest mechanically. Harvesting losses steadily increase as corn is allowed to mature to lower moisture levels as follows:

Percent moisture	Percent loss
26	8.0
22	12.0
20	13.5
18	17.0
16	20.0

Field losses decrease to about 7.5 percent by harvesting at 28-percent moisture. At this point, the solid-matter content of corn is the highest. Once corn has matured to 26-percent moisture, the ear ceases to draw nourishment from the stalk, but moisture content is still high enough for respiration to continue. The respiration, or breathing, process consumes solids, thus increasing dry-matter losses.

Corn dries (loses moisture) at about three-fourths of a percent per day from the time it dents until it reaches about 25-percent moisture (1). Corn at 25-percent moisture is normally unaffected by weather. However, after the moisture content drops below 25 percent, weather becomes a major factor. If weather is favorable, corn in the 20- to 25-percent moisture range dries at an average daily rate of 0.5 percent. If the humidity is high, drying can take a month or more to reach 15.5-percent moisture. When corn is picked after remaining in the field over the same period, about 20 percent of the yield may be lost by conventional field shellers. Of this loss, one-third is in the form of ears and two-thirds is shelled kernels. Generally, for every two kernels of corn per square foot found in the field after harvest, a 1-bushel per acre field loss may be assumed.

For corn yielding 100 bushels per acre and valued at $2.50 per bushel, a 20-percent loss equals $50 per acre or 50 cents per bushel. At this rate, savings in field losses would more than cover the cost of drying.

Mixing Wet and Dry Corn

A study by Sauer and Burroughs (13) concluded that mixing wet and dry corn is a reasonably efficient way to save on drying costs, and a practice that may supplement limited drying system capacity. The practice of mixing wet and dry grain also may serve as an adjunct to low-energy, natural air drying systems. Equilibration of the wet and dry corn is rapid, usually more than 80-percent complete within 24 hours.[2] Within 48 hours, equilibration averages 94-percent complete.

Blending does not cause quality loss in corn, provided the average moisture content of the blend is low enough to prevent fungal growth. However, some caution must be taken by both seller and buyer when blended corn is immediately marketed. If the wet corn is not thoroughly mixed with the dry corn, it is possible to get a wide range of moisture and test weight readings. However, if the corn is taken from the drying bin and placed in a storage bin, the amount of stirring may not be as critical. With continued aeration, no quality problems should be anticipated.

Another advantage of mixing wet and dry corn is the speed with which a farmer can reduce high moisture levels. The average moisture content reaches 15.5 percent about 1 week sooner than the top layer reaches this moisture level. (This assumes that 25-percent moisture corn is placed in the bin on October 15 in Dodge City.) If the corn can be moved from the drying bin when the average moisture reaches 15.5 percent, and the wet and dry kernels are mixed in the process, chances for mold growth may be greatly reduced.

---

[2] The term, equilibration, refers to the physiological process (in this case corn's) whereby all corn, wet and dry, reaches the same percentage of moisture by the transfer of moisture from wet kernels to dry kernels.

Fan and Heat Strategies

Three strategies were considered for drying:

1. A 5-hp axial fan for moving heat from the solar collector into the corn bin and for longer term aeration. (A 5-hp fan is generally considered the largest practical fan size for aerating grain.)
2. A 10-hp axial fan for moving heat from the solar collector into the corn bin. (This fan size would be more expensive to operate, but it could produce a higher airflow and increase the probability of successful drying. For aeration, a fan of this size would normally be operated only a few minutes each day.)
3. A companion heater with option No. 1. Such heaters are capable of producing 2 million or more Btu's per hour and an airflow of 12,000 cubic feet per minute (cfm) at a temperature of 140° F.

Decisions to choose either of the first two options should be based on a comparison of the cost of owning and operating the solar collection system and the alternative (conventional) drying method. The value of anticipated losses in years of poor solar drying weather, as well as direct costs, must be taken into account.

The decision to choose a 10-hp fan over a 5-hp fan also must take into account the value of improved quality corn due to the larger fan as well as the added investment cost. At 1980 prices, the added cost of the larger fan amounted to 12 cents a bushel per year for the grain drying system selected for this study. If drying only one binful of corn, the added cost of the larger fan would likely exceed returns on better quality corn, even if the larger fan is needed every year.

If the third strategy is chosen, the decision should be based on the added cost of the heater versus savings in corn quality. The cost of owning and operating a supplemental heater must be compared with the loss due to corn deterioration. Since the heater would be used only sparingly, a 20-year lifespan may be assumed. The annual fixed cost of owning a backup heater would equal about 4.5 cents per bushel. Operating costs, assuming the use of an electric heater, would amount to nearly 13.5 cents per bushel. The economic loss due to corn deterioration, assuming a reduction in grade from No. 2 to No. 3 in 5 of 10 years, would be only 5 cents (table 2). Thus, it would not pay the farmer to maintain a backup unit for the system modeled in this study, given current fuel costs and discount schedules.

Instead, it would occasionally benefit farmers to sell lower grade corn. Therefore, as fuel costs and grain dryer investment costs (including solar collector costs) increase relative to corn prices, buyers should anticipate more and more poor-quality corn, unless discounts for low-quality corn are raised. These conclusions may be applied to all crops presently dried in the west central Great Plains. In fact, in this region, where postharvest drying conditions are relatively favorable compared with other corn-producing areas, the use of any artificial drying method other than natural air is questionable.3/

Capital Investment

Total investment for an 8,000-bushel system is estimated to be $26,017, or $3.38 per bushel (table 3). Components of the system and their percentages of total investment are:

Component	Percentage of total investment
Bins and accessories	62.3
Handling equipment	27.1
Aeration equipment	3.8
Solar collector and equipment (2 months)	4.3
Quality control	2.5
Total	100.0

Only one-sixth of the total cost of the solar collector and related equipment was included in this analysis. The remaining cost is assumed to be allocated to other farm use.

According to Linville (fig. 2), who studied in-bin systems ranging from 10,000 to 120,000 bushels (10), economies of scale exist in grain-drying and storage systems. The system designed for this study appears to be in line with the Linville investment curve. Thus, larger systems should reflect a considerably lower investment cost per bushel, particularly for bins and handling equipment. However, large-sized solar-supplemented, natural air drying systems may not achieve the maximum economies of scale shown in the Linville investment curve if the solar-supplemented system includes two or more small portable collectors attached in tandem.

SIMULATION MODEL

The FALDRY simulation model is used to predict the probability of economic loss due to quality deterioration of shelled corn

---

3/ Infield losses caused by corn borer infestation may be high enough in some cases to warrant harvesting and drying high-moisture corn.

Table 3--Capital investment costs of an 8,000-bushel grain-drying and storage system using solar energy to supplement natural air drying, 1980

Item	Investment cost
	Dollars
Bins and accessories:	
Bins 1/	7,120
Floors, perforated 2/	2,877
Foundations 3/	1,599
Spreaders 4/	1,041
Labor	2,912
Miscellaneous (including fences and electric hookup)	655
Subtotal	16,204
Handling equipment:	
Elevating system 5/	3,631
Auger tube and screw 6/	2,088
Unloading motor	714
Grain cleaner	413
Labor	207
Subtotal	7,053
Aeration equipment:	
Fan 7/	660
Transitions, ducts, and collars	330
Subtotal	990
Solar collector and equipment:	
Collectors 8/ (2 months)	639
Transitions, ducts, and collars	480
Subtotal	1,119
Quality control:	
(Humidistat, thermostat, manometer, and thermometer)	651
Total	26,017

1/ Bin includes roof, 20 in. x 20 in. manway, anchor bolts, seam and base sealer, and base angle ring. 2/ Perforated floor, including plenum and metal supports. 3/ 18 in. of concrete. 4/ 0.25-hp motor. 5/ 6 in. electric auger designed at 30° angle for average sloped bin roofs; discharge directly into bin. 6/ 6 in. auger with 13 ft. vertical unloading auger electrically driven with motor mount connector sleeve and adjustable swivel spout. 7/ Electric heater and 5-hp 25 in. axial fan. Motor has prewind magnetic motor starter, overload relays, on-off breakers for each heat stage, interlock circuit between fan and heater, and is weather-protected. 8/ Flat-plate collectors.

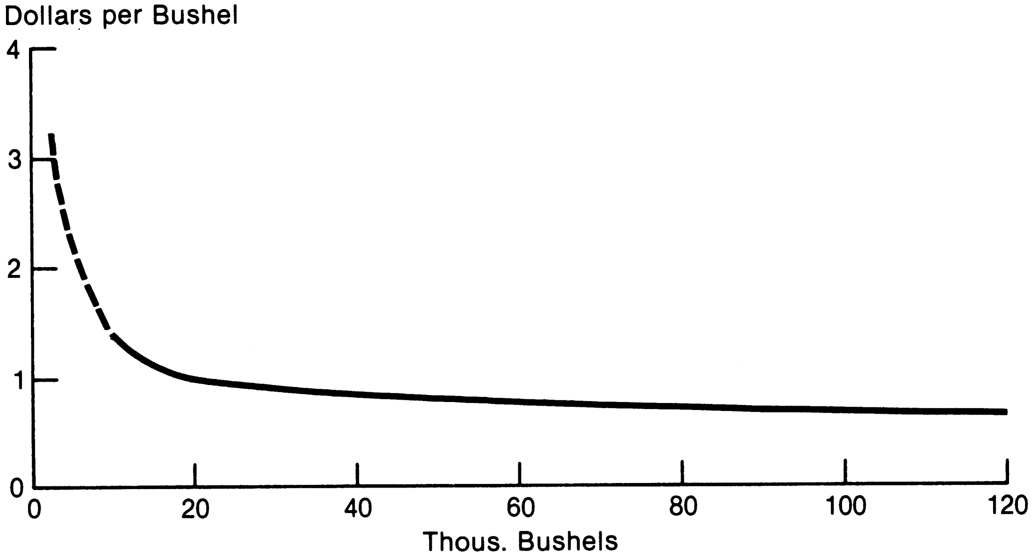
(18). FALDRY is a deterministic model designed to simulate a system of one to six grain bins equipped with perforated floors and axial fans. Given bin specifications, fan sizes, grain pack factor, and harvest flow rates, the model: (1) allows total layer-filling flexibility by enabling each bin to accept any specified quantity of grain, (2) determines the air delivery rate and the resulting heat rise of the air based on fan and bin specifications and daily quantity of grain in the bin, (3) predicts the grain-moisture profile, drying time, and electricity usage, and (4) simulates a complete drying season. A series of simulation runs illustrate the effect of these factors and the addition of solar-supplemented heat on the drying process.

For batch-in-bin drying, initial runs showed that a 5-hp fan produced an airflow at 19.1 cfm per square foot of bin floor area. A 10-hp fan was required in years when drying was not accomplished without excess dry-matter decomposition, increasing the airflow to 24.3 cfm per square foot of bin floor area. These airflow rates represented 1.8 and 2.2 cfm per bushel, respectively.

For layer-in-bin drying, the initial airflow was 26.6 cfm per square foot of bin floor area. Airflow decreased as successive layers of shelled corn were added, eventually reaching the same

Figure 2

Total Investment Curve for an In-Bin Storage and Drying System, Various Volumes



Source: (*10*).

rate as the batch-in-bin system when the drying bin was completely filled. A 10-hp fan was not modeled for layer-in-bin drying.

The FALDRY model predicts both the average amount of deterioration and the amount in each layer of the bin after each day of drying. System failure is predicted as the point where dry-matter deterioration reaches 0.5 percent or more in the top layer. At this level of deterioration, corn quality of the entire bin is assumed to lose one grade point.

SYSTEM DESIGN

Batch methods, both in-bin and outside-bin systems, are the most common type of onfarm grain dryers. Outside-bin dryers use high temperatures and do not require bin space for the drying process. Batch-in-bin and layer-in-bin drying systems using lower temperatures are well adapted to a fast harvest so long as enough drying/storage space is available.

Batch-in-bin systems require more fan power than layer-in-bin systems because of greater grain depths. Therefore, a layer-in-bin system may be better suited to current and emerging farming practices that use conventional fuel by minimizing both the time and fuel requirements for drying. A recent grain dryer survey in Kansas showed that layer-in-bin systems have been the most frequent type of in-bin dryers purchased by farmers since 1976 (6).

A capacity of 8,000 bushels is assumed for the simulated drying/storage system. The bin configuration includes three 18-foot diameter bins, each 15 feet high. To achieve compatibility with low-temperature drying and to provide for a manageable collector size, three small bins are designed into the system instead of one large bin. Each bin has a capacity of about 2,700 bushels. Grain depth of each batch is about 13 feet. Given a 100-bushel per acre corn yield, a system of this size can handle about 80 acres of corn.4/ It is further assumed that the flat-plate solar collectors, being a part of a multiple use system, are available for 2 months each fall to dry high-moisture corn.

Bin size is kept constant for both drying methods. For layer-in-bin drying, results of the model are applicable whether the corn is stored in alternate bins each day or one bin is filled every other day.

4/ There should be no economic or technical barriers to enlarging this system through duplication. Substantial economies of scale may exist in larger grain storage systems. Preliminary research shows some economies of scale in solar collectors and related equipment (4).

Collector Sizing

Sizing of solar collectors was based on the following formula (11):

$$\frac{1.1 \times \begin{array}{c}\text{collector}\\ \text{airflow}\\ \text{(cfm)}\end{array} \times \begin{array}{c}\text{average}\\ \text{temperature}\\ \text{rise (F°)}\end{array} \times \begin{array}{c}24\\ \text{(hr/day)}\end{array}}{\begin{array}{c}\text{average solar}\\ \text{energy}\\ \text{(Btu/day ft}^{2}\text{)}\end{array} \quad \begin{array}{c}\text{average collector}\\ \text{efficiency}\\ \text{(percent)}\end{array}} = \text{collector area}$$

A portable flat-plate collector was assumed, as was adjustment of the collector's airflow, to make it usable for home heating or other uses.

To obtain a 3-degree (F) temperature rise above the ambient air temperature, 363 square feet of collector surface was needed, or a 10- by 36-foot collector. That is, the ratio of collector surface to bin floor area was nearly 1.5 to 1 for the Dodge City area, assuming a 55-percent average collector efficiency, an easily obtainable percentage for homemade collectors.

Air System

Airflow rate is the most important factor in designing and operating batch-drying systems. A minimum airflow requirement for 24- to 26-percent moisture corn is 2 cfm per bushel. In poor drying weather, higher airflow is necessary to prevent spoilage. According to Converse, a drying fan and motor should be selected to provide an airflow volume of 30 cfm per square foot of the cross-sectional bin area (3). A 5-hp axial fan will produce the cfm required for an 18-foot diameter bin, assuming as much as 3 inches of static pressure (SP).[5] A 5-hp fan may produce up to 5,000 cfm with 4 inches SP.

For this study, a 5-hp axial fan was used both on the solar collector for drying and later on the bin for aeration. A 5-hp fan is considered optimum since it is the largest size normally used for aeration following drying and the smallest that can be used on the collector considering airflow requirements. A 10-hp fan was considered for use in inclement years as an alternative to a backup heater. Both fans were assumed to carry a thermostat and humidistat.

A drying system must be designed to reduce the moisture content of high-moisture corn in less than 1 week if temperatures are high (table 1). However, once the corn is dried to 20-percent moisture, and grain temperature is below 60°F, time is less critical. A solar-supplemented, natural air drying system

---

[5] Static pressure is a measure of air pressure usually expressed in inches of water column (w.c.). Fans are rated in terms of static pressure and total air volumetric airflow.

could take a total of 30 or more days without serious grain quality loss.

SIMULATION RESULTS

Farmers will not benefit economically from solar-supplemental heat, using either batch-in-bin or layer-in-bin drying. Increased deterioration, longer drying time, and overdrying during batch-in-bin simulations cut into profits. The layer-in-bin method showed improved results but was plagued by unacceptable overdrying.

Batch-in-bin Drying

Two solar drying strategies were simulated for batch-in-bin drying. One was a single-bin strategy that assumed the corn was dried and stored in the same bin. The other was a transfer strategy that assumed the corn was dried to a 15.5-percent average moisture content and then transferred to a storage bin. For each strategy, September 15 to October 15 were the simulated harvest dates. Corn moisture was allowed to vary from 25 to 22 percent, and both 5- and 10-hp fans were used. For each simulation run, three levels of temperature rises were assumed. The first level assumed only the heat generated from the fan. The second level assumed 3 degrees (F) additional solar heat, and the third, 6 degrees (F) additional heat supplied by a solar collector. Total temperature rises, including fan-generated heat were, 2.7, 5.7, and 8.7 degrees (F), respectively.

Probabilities of success were determined for each simulation run, a successful year being one in which corn was dried to 15.5-percent moisture content without deterioration of the top layer reaching 0.5 percent.

Single-bin Strategy

The single-bin strategy may be a more realistic choice than a tranfer strategy on small farms with few bins, for farms with widely dispersed bins, and in cases where corn is custom harvested. With larger volumes of corn being stored on farms until well after harvest, the opportunity decreases for filling each bin more than once. Also, the uncertainty of drying time associated with low-temperature solar drying suggests a single fill.

September 15 Harvest Date. The time required to dry the top layer of corn to 15.5-percent moisture averaged 23 days using the 5-hp fan only, and 19 days when 6 degrees (F) of solar heat were applied (table 4). The temperature rise led to a decrease in corn deterioration 70 percent of the time and an increase 30 percent of the time. Chance of success (at or below 0.5-percent loss) was only 1 in 20 at all levels of temperature rise.

A second simulation run was made, assuming the use of a 10-hp fan. Even with larger airflow and a slightly higher tempera-

Table 4--Days required to dry bin average and top layer to 15.5-percent moisture, and accumulated deterioration, assuming September 15 harvest date, 25-percent moisture corn, and 5-hp fan

Year	Temp. rise 2.7 degrees (F)				Temp. rise 5.7 degrees (F)				Temp. rise 8.7 degrees (F)			
	Average		Top layer		Average		Top layer		Average		Top layer	
	Days	Deterioration	Days	Deterioration	Days	Deterioration	Days	Deterioration	Days	Deterioration	Days	Deterioration
	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
1955	20	0.625	25	1.681	15	0.496	22	1.502	13	0.464	19	1.281
1956	8	.154	14	.379	7	.154	13	.393	7	.163	12	.410
1957	15	.307	21	.777	13	.284	19	.753	11	.260	18	.736
1958	16	.482	22	.940	14	.475	20	.933	12	.448	19	.989
1959	18	.470	25	1.010	13	.445	21	.981	11	.418	18	.997
1960	16	.434	22	1.123	14	.411	20	1.065	12	.373	18	1.006
1961	16	.278	22	.574	15	.286	21	.603	13	.268	19	.623
1962	23	.909	30	2.654	19	.749	26	2.174	15	.615	22	1.597
1963	15	.657	21	1.379	13	.634	19	1.377	12	.617	18	1.392
1964	19	.531	25	.947	17	.507	23	.989	15	.475	21	1.049
1965	24	.558	30	1.150	20	.474	26	1.136	18	.438	24	1.066
1966	18	.461	25	.980	16	.438	22	.943	14	.413	20	.949
1967	14	.351	20	.877	12	.344	19	.826	10	.306	17	.796
1968	12	.300	18	.756	11	.300	17	.785	10	.287	16	.735
1969	17	.805	24	2.183	16	.746	21	1.944	14	.672	20	1.845
1970	18	.573	25	1.286	16	.524	22	1.147	14	.512	20	1.202
1971	18	.295	24	.772	15	.226	21	.770	13	.184	19	.735
1972	14	.392	20	.839	11	.356	18	.842	10	.341	16	.858
1973	21	.554	27	1.416	19	.519	25	1.272	16	.450	22	1.236
1974	16	.386	23	.907	15	.385	21	.817	13	.374	19	.817
Average	17	.476	23	1.132	15	.438	21	1.063	13	.404	19	1.016
Probability of success (≥0.5%)		60		5		70		5		80		5

ture rise due to added heat from the larger fan, the probabilities of success did not increase. In poor drying years, the top layer deterioration still exceeded the 0.5-percent acceptable maximum.

These results indicated an aberration in the climatological data for the region. The comparison showed that, although temperature differences were not as pronounced, average daily humidity was considerably higher on the September 15 drying date than on October 15. Thus, in the west central Great Plains, low-temperature solar batch drying of 25-percent moisture corn could not be accomplished starting September 15.

Seeking the moisture content at which solar-supplemental heat might make the difference between success and failure for the single-bin strategy, a third set of simulations was run assuming 23-percent moisture. Results indicated that corn must be below 23-percent moisture for successful low-temperature solar batch drying, if harvested on September 15. The probability of success was increased to 60 percent with temperature increases of 2.7 degrees and 5.7 degrees (F) and to 70 percent with an 8.7-degree (F) temperature rise (table 5). However, adding solar-supplemental heat to natural air not only failed to prevent deterioration, but actually increased it in the top layer 35 percent of the time.

In a fourth simulation run, the effects of harvest moisture level were analyzed. For a selected poor drying year, ability to solar dry 22- and 25-percent moisture corn was compared, assuming the 5-hp fan (table 6). Results indicated a high degree of success when drying 22-percent moisture corn, because drying time was reduced and supplemental heat was unnecessary. The run also predicted a sharp increase in grain deterioration in years of inclement postharvest weather, leading to potential serious economic losses due to mold growth.

The feasibility of harvesting corn in September was not pursued because, in a practical sense, low-moisture corn cannot always be harvested then in the region studied. Most production in the area is on irrigated land, and only about 50 percent of the corn is mature (down to 25- to 26-percent moisture) by September 15.

October 15 Harvest Date. Simulated solar drying averaged 4 to 10 days longer than for the September 15 harvest date, although the probability of success was much greater. The simulated run for 25-percent moisture corn gave a 70-percent probability of success for a 2.7-degree (F) temperature rise and a 75-percent chance of success for the two higher temperatures (table 7). Even by assuming the later harvest date, the top layer could

Table 5--Days required to dry bin average and top layer to 15.5-percent moisture, and accumulated deterioration, assuming September 15 harvest date, 22-percent moisture corn, and 5-hp fan

Year	Temp. rise 2.7 degrees (F)				Temp. rise 5.7 degrees (F)				Temp. rise 8.7 degrees (F)			
	Average		Top layer		Average		Top layer		Average		Top layer	
	Days	Deterioration	Days	Deterioration	Days	Deterioration	Days	Deterioration	Days	Deterioration	Days	Deterioration
	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
1955	9	0.354	19	0.482	8	0.351	16	0.460	7	0.321	14	0.456
1956	6	.144	12	.219	6	.156	11	.227	5	.142	11	.237
1957	12	.257	19	.394	11	.258	17	.383	10	.256	16	.372
1958	13	.434	20	.508	11	.423	18	.530	10	.414	16	.530
1959	11	.409	18	.497	9	.346	16	.496	8	.322	14	.496
1960	12	.370	18	.454	10	.341	16	.434	7	.250	14	.419
1961	14	.266	20	.328	11	.241	18	.334	10	.249	15	.329
1962	20	.769	27	.941	16	.697	23	.823	13	.590	19	.765
1963	13	.617	19	.725	12	.625	17	.731	10	.571	16	.742
1964	18	.503	23	.538	14	.398	20	.546	12	.394	18	.516
1965	22	.497	27	.548	18	.433	24	.509	15	.397	21	.462
1966	15	.412	22	.486	13	.382	19	.487	11	.335	17	.481
1967	11	.338	18	.420	9	.297	16	.418	8	.288	14	.420
1968	10	.291	16	.383	9	.298	15	.395	8	.261	14	.378
1969	15	.626	21	.852	14	.618	19	.786	12	.548	17	.353
1970	16	.478	22	.602	14	.453	20	.579	12	.443	18	.557
1971	15	.270	21	.377	13	.210	19	.347	12	.233	17	.315
1972	10	.310	17	.423	9	.300	15	.431	8	.296	14	.429
1973	19	.539	25	.600	15	.435	21	.559	12	.394	19	.526
1974	14	.344	21	.418	12	.329	18	.417	12	.321	17	.425
Average	14	.411	20	.510	12	.380	18	.471	10	.351	16	.460
Probability of success (≥0.5%)	75		60		85		60		85		70	

not be solar dried fast enough in years of bad weather to prevent spoilage. More important, adding 3 degrees (F) increased the accumulated grain deterioration in the top layer 70 percent of the time. Effects of added solar heat on the deterioration rate are shown in figure 3.

Fan size was increased to 10 hp for years that deterioration exceeded 0.5 percent in the first October 15 run, raising the probability of success for all temperature levels to 85 percent.

The time required to dry the top level to 15.5-percent moisture was reduced by 1 to 13 days for the years of failure, assuming the 5-hp system.

For a selected poor-drying year, solar drying was simulated for corn harvested at 22- to 25-percent moisture. As beginning

Table 6--Effect of early maturity on grain deterioration, given unfavorable postharvest drying weather, September 15 harvest date, 5-hp fan

Temperature rise and grain deterioration	Corn moisture (percent)		Decline in deterioration
	25	22	
		Percent	
2.7 degrees (F) temperature rise:			
Average deterioration	0.586	0.207	-0.379
Top layer deterioration	1.150	.375	-.775
5.7 degrees (F) temperature rise:			
Average deterioration	.514	.177	-.337
Top layer deterioration	1.136	.336	-.800
8.7 degrees (F) temperature rise:			
Average deterioration	.473	.159	-.314
Top layer deterioration	1.066	.324	-.742

Table 7--Days required to dry bin average and top layer to 15.5-percent moisture, and accumulated deterioration, assuming October 15 harvest date, 25-percent moisture corn, and 5-hp fan

Year	Temp. rise 2.7 degrees (F)				Temp. rise 5.7 degrees (F)				Temp. rise 8.7 degrees (F)			
	Average		Top layer		Average		Top layer		Average		Top layer	
	Days	Deterioration	Days	Deterioration	Days	Deterioration	Days	Deterioration	Days	Deterioration	Days	Deterioration
	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent	No.	Percent
1955	12	0.191	19	0.233	11	0.200	18	0.252	10	0.211	16	0.274
1956	16	.397	24	.451	13	.334	21	.472	12	.345	19	.475
1957	33	.441	39	.504	23	.408	31	.442	18	.383	26	.439
1958	11	.188	20	.239	13	.184	18	.255	9	.204	16	.269
1959	19	.321	28	.368	14	.273	23	.375	12	.281	20	.373
1960	24	.449	32	.484	19	.436	27	.500	17	.461	23	.535
1961	13	.181	23	.282	11	.172	19	.279	10	.183	18	.277
1962	17	.289	25	.330	14	.282	22	.347	13	.284	19	.343
1963	19	.812	26	.899	16	.832	23	.918	14	.836	20	.960
1964	19	.461	28	.538	16	.379	22	.490	13	.293	20	.460
1965	20	.550	29	.693	17	.528	25	.662	15	.517	21	.660
1966	15	.161	24	.204	13	.150	22	.217	12	.147	19	.227
1967	11	.132	19	.173	10	.139	18	.184	9	.142	16	.196
1968	16	.263	24	.336	15	.272	21	.345	13	.269	19	.345
1969	29	.443	37	.481	25	.425	31	.485	22	.404	28	.464
1970	26	.323	35	.359	23	.316	29	.363	18	.313	26	.367
1971	23	.512	30	.543	19	.535	26	.575	15	.533	23	.612
1972	24	.273	31	.347	21	.258	27	.297	17	.253	24	.295
1973	12	.263	20	.315	11	.275	18	.337	10	.286	17	.362
1974	28	.748	33	.757	18	.667	27	.747	15	.599	22	.761
Average	19	.370	27	.427	16	.353	23	.405	14	.347	21	.435
Probability of success (≥0.5%)		80		70		80		75		80		75

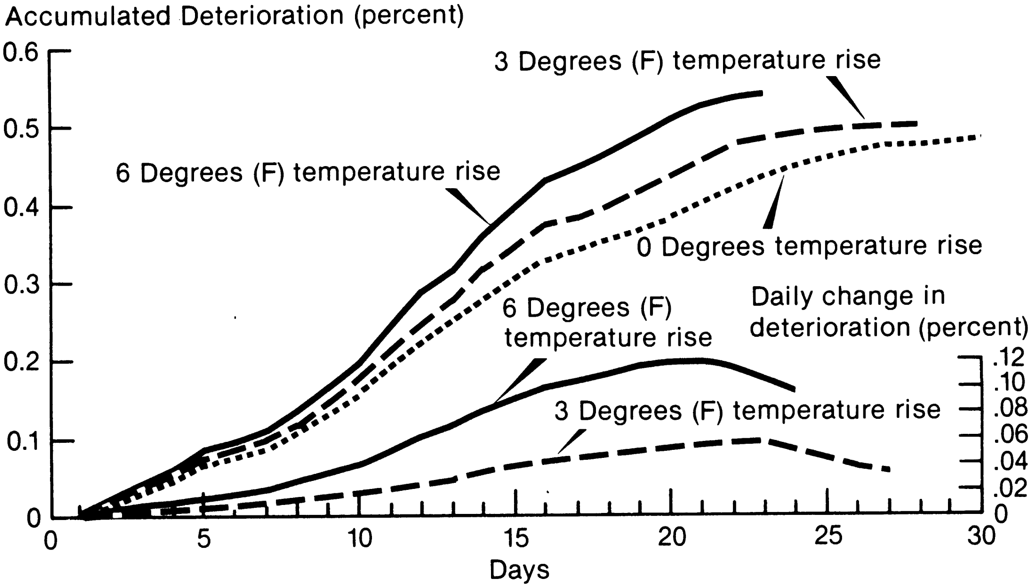
moisture content was lowered, deterioration of the top layer was reduced as follows:

Percentage of moisture	Temperature rise (degrees (F))		
	2.7	5.7	8.7
	Percent deterioration		
25	0.693	0.662	0.660
24	.485	.480	.477
23	.351	.346	.345
22	.253	.250	.250

Regardless of harvest dates, the single-fill strategy consistently produced overdried corn. To reduce the top layer to 15.5-percent moisture, the bin average moisture frequently reached 11.5 to 12 percent. This practice, of course, would lead to profit losses. A bushel of corn, at 11.5-percent moisture, wet basis, weighs about 53.5 pounds. Assuming corn valued at $2.50 per bushel (4.5 cents per pound), this strategy could result in a loss of 11.2 cents per bushel due to excessive moisture loss alone.

Figure 3

Typical Effects of Added Heat on Top Layer Deterioration, Dodge City, Kansas



Transfer Strategy

The strategy of transferring partially solar dried corn to a storage bin may be preferable to the single-fill strategy. Wet and dry corn--corn above and below 15.5-percent moisture--is assumed to be well mixed at the time of transfer with equilibration taking place in about 2 days. Transferring corn to a storage bin accomplishes two things: it sharply reduces the number of days that the top layer(s) of grain remains at the high-moisture content, and it minimizes the number of days the drying bin is used per batch.

September 15 Harvest Date. Whereas deterioration consistently exceeded 0.5 percent while waiting for the top layer of September 15 harvested corn (25-percent moisture) to reach 15.5-percent moisture content, the probability of success was much greater if the corn was held in the drying bin only until the average moisture content reached 15.5 percent. The probability of success, assuming a 5-hp fan, was 60 to 80 percent for these temperature levels (table 4). The number of drying days was reduced as follows:

Strategy	Temperature rise (degrees (F))		
	2.7	5.7	8.7
	Average number of days		
Top layer dried to 15.5 percent	23	21	19
Bin average dried to 15.5 percent	17	15	13
Savings in time	6	6	6

Even with this time savings, the allowable storage time for shelled corn was exceeded in some years. Thus, it can be concluded that it is not advisable to use low-temperature solar drying when following either of the batch-in-bin drying strategies if the farmer desires to harvest high-moisture corn on September 15 in the west central Great Plains.

For the simulation run assuming a September 15 harvest date and 23-percent moisture corn, the transfer strategy yielded an 85-percent probability of success when solar heat was added (table 5). This compared with a 75-percent probability without additional heat and only a 60-percent probability of success for the single-bin strategy. The addition of 3 degrees (F) of heat increased the probability of successful drying from 75 to 85 percent. The addition of 6 degrees (F) of solar heat failed to improve the probability of success. The time required for the average moisture content to reach 15.5 percent, assuming a 2.7-degree (F) temperature rise (0 degrees added solar heat), averaged 14 days, 6 days faster than for the single-bin strategy. The addition of 3 degrees (F) solar-supplemented heat reduced the drying time 2 additional days. Both cumulative deterioration and days of drying time were reduced when lower moisture grain was harvested (fig. 4).

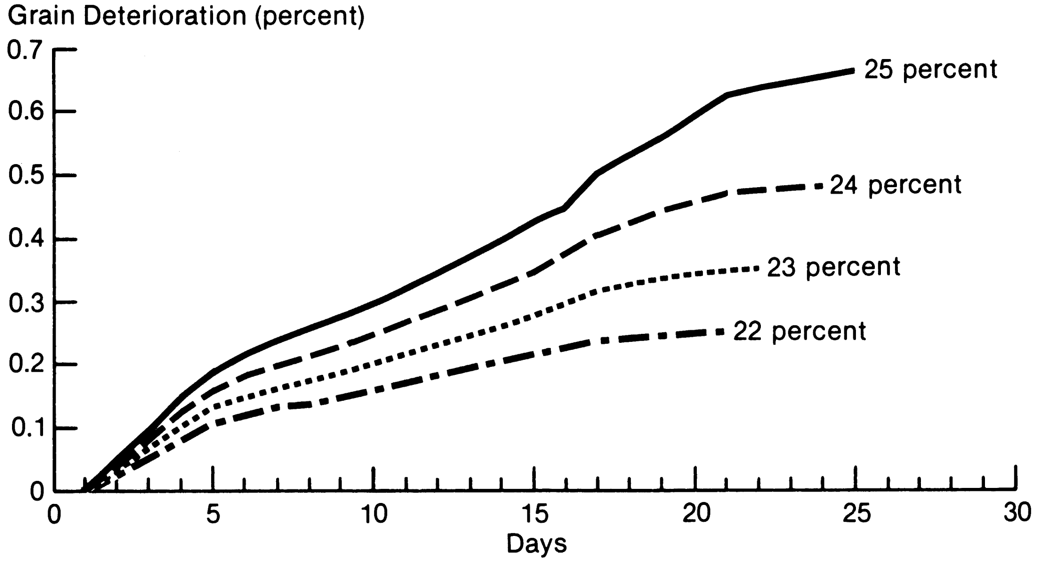
Simulation runs assuming 22-percent moisture corn showed a 100-percent probability of successful drying without adding heat beyond that produced by the 5-hp fan. About 7 fewer days were required to dry 22-percent moisture corn than 25-percent moisture corn.

October 15 Harvest Date. The simulation runs for an October 15 harvest date, assuming 25-percent moisture corn, resulted in an 80-percent probability of success regardless of the temperature rise (table 7).

By increasing the fan size to 10 hp, the probability of successful drying increased to 90 percent when no heat was added. The probability of success increased to 95 percent in both solar heat situations.

Figure 4

Effects of Corn Moisture Content on Cumulative Deterioration of Top Layer in Bin and Drying Time[1]



[1] Simulated results based on October 15 harvest date, 5-hp fan, and 5.7 degrees (F) temperature rise.

The number of days required to dry the average bin content of 15.5-percent moisture was sharply lowered by using the transfer strategy:

Strategy	Temperature rise (degrees (F))		
	2.7	5.7	8.7
	Average number of days		
Top layer dried to 15.5 percent	27	23	21
Bin average dried to 15.5 percent	19	16	14
Savings in time	8	7	7

When following the transfer strategy, the FALDRY model suggests that there is little advantage in delaying harvest until corn is below 25-percent moisture. Likewise, no advantage exists for solar-supplemented heat when harvesting corn in the region on October 15. When weather conditions in the west central Great Plains are conducive to drying shelled corn, it can be dried with natural air. If weather conditions are not conducive to drying, a few degrees of supplemental solar heat will not help. In fact, in most years, a few degrees of supplemental heat increases deterioration in the top layer of the drying bin (fig. 3).

Thus, the simulation results suggest that achieving a high degree of low-temperature solar drying success relies on a corn harvest in the west central Great Plains after September 15 unless the moisture content is below 23 percent. The results also show that a solar-supplemented system would work in a single-bin strategy, but a natural air system will perform just as well given proper airflow. The grain temperature and the number of days required to dry the average moisture content of the corn to 15.5 percent, and the resultant accumulated top layer deterioration, are shown in appendix tables 4 and 5.

Layer-in-bin Drying

A layer-in-bin drying method could be used on farms with two or more drying/storage bins or when a fast harvest is not critical. As the concept suggests, successive layers of grain are placed in a drying bin until it is filled, assuming that the corn continued to dry 0.5 percent per day in the field before harvest. Layer depths are determined by the cubic-feet-per-minute output of the drying fan and the moisture of the grain to be solar dried.

Proper layer depth is determined by checking the bin for the highest point dried on the morning following the placement of the wet grain (2). This is called the drying point. If it is within 6 inches of the top of the layer, the system--fan and depth of layer--is in balance.

Years of exceptionally high top layer deterioration were selected from the previous runs to simulate layer-in-bin drying. One year--1963--typified the improved performance of layer-in-bin drying over batch-in-bin drying (table 8). The data show the importance of placing high-moisture grain in bins at only shallow depths when using low-temperature solar drying.

According to the results of the simulation runs for 1963, a poor drying year, layer-in-bin drying reduced the time required to dry the top layer of shelled corn to 15.5-percent moisture by 2

Table 8--Comparison of shelled corn deterioration, by method of solar drying and temperature rise 1/

Drying strategy	Temperature rise (degrees (F))		
	2.7	5.7	8.7
Batch-in-bin:			
Average deterioration	0.478	0.463	0.454
Top layer deterioration	.899	.918	.960
Layer-in-bin (2-day fill interval):			
Average deterioration	.211	.188	.169
Top layer deterioration	.303	.300	.298
Layer-in-bin (5-day fill interval):			
Average deterioration	.063	.049	.040
Top layer deterioration	.043	.038	.033

1/ Simulated data for October 15, 1963 harvest, a year of exceptionally poor drying weather in the Dodge City region.

to 5 days, depending on the interval between fillings:

Strategy	Temperature rise (degrees (F))		
	2.7	5.7	8.7
		Days	
Batch-in-bin	26	23	20
Layer-in-bin			
Fill interval:			
2-day	24	20	18
5-day	21	17	16

Results of five simulation runs, shown in table 9, indicate two things: that 25-percent moisture corn can be successfully dried every year, even if harvested early in the fall; and that solar-supplemental heat is advantageous, decreasing both drying time and top layer deterioration.

The simulation runs for layer-in-bin drying reflected no increases in top layer deterioration when solar heat was added. However, this method, like the batch-in-bin strategy, resulted in appreciable overdrying.

Thus, while the layer-in-bin strategy appeared to yield better results than the batch-in-bin strategy, neither yielded the results expected for a region with abundant solar radiation. In this region, farmers may benefit most by using no supplemental heat.

ANNUAL COSTS

Annual ownership and operating costs of the grain drying/storage system are estimated to be 66.8 cents per bushel. These costs reflect 100-percent utilization of the storage space for a 6-month period each year.

Fixed Costs

Fixed costs totaled 53.2 cents per bushel and accounted for 80 percent of all costs (table 10). The cost of the solar collector and equipment was calculated at 2.5 cents per bushel for 2-months use. This cost included a 5-hp fan and related ductwork. In reality, this equipment would be necessary just to operate the natural air system. As shown in table 3, the fans cost $660, or two-thirds of the total investment charged for the solar collector and related equipment. Thus, the use of solar energy as a supplement to natural air added only the cost of the collectors and the transition equipment for connecting the fans to the solar collectors. This added investment of $1,119 resulted in annual fixed costs totaling 2.5 cents per bushel.

Table 9--Predicted drying results, assuming layer-in-bin strategy, selected harvest dates

Harvest date	Filling interval	Beginning moisture content by layer			Days to dry by temperature rise			Top layer deterioration		
		1	2	3	0 degrees (F)	3 degrees (F)	6 degrees (F)			
	Days	Percent			Days			Percent		
October 15, 1963	5	25	22.5	20	21	17	16	0.043	0.037	0.033
October 15, 1963	2	25	24	23	24	20	18	.303	.300	.298
October 1, 1963	2	25	24	23	13	12	12	.104	.100	.099
October 1, 1965	2	25	24	23	20	18	16	.238	.189	.167
October 1, 1974	2	25	24	23	22	20	18	.218	.202	.193

Table 10--Fixed costs of owning an 8,000-bushel grain-drying and storage system, using solar energy to supplement natural air drying, 1980

Item	Cost
	Cents per bushel
Bins and accessories:	
Depreciation	8.7
Interest on investment	12.2
Taxes	3.8
Insurance	1.6
Subtotal	26.3
Handling equipment:	
Depreciation	6.5
Interest on investment	5.3
Taxes	1.7
Insurance	.7
Subtotal	14.2
Aeration equipment:	
Depreciation	.9
Interest on investment	.7
Taxes	.2
Insurance	1/
Subtotal	1.8
Solar collector and equipment (2 months):	
Depreciation	1.3
Interest on investment	.8
Taxes	.3
Insurance	.1
Subtotal	2.5
Quality control:	
Depreciation	.8
Interest on investment	.5
Taxes	NA
Insurance	NA
Subtotal	1.3
Total	46.1

NA = Not applicable.

1/ Less than 0.05 cent.

Variable Costs

Variable costs totaled 13.6 cents per bushel, or 20 percent of all costs (table 11). Costs related to the solar collector included the fan operation cost, labor, and repairs. However, as explained previously, the fan would have been operated regardless of solar collector use. Therefore, the only added variable costs charged to the solar collectors were the repair and labor costs, totaling 2.4 cents per bushel.

Total Costs

In these cost analyses, the bin, handling, and quality control costs were assumed to be incurred by the storage function, even if the corn had not been dried. The fixed and variable costs directly associated with the solar collector totaled only 4.9 cents per bushel. This cost equaled about one-half of the discount (10 cents per bushel) had corn gone out of condition and been graded No. 3 instead of No. 2.

Table 11--Variable costs of operating an 8,000-bushel grain-drying and storage system, using solar energy to supplement natural air drying, 1980

Item	Cost
	Cents per bushel
Insurance	1.1
Insect control	.5
Handling	.8
Aeration	.6
Solar drying (electricity, 3.0; labor, 0.4; and repair, 2.0)	5.4
Interest on operating capital	.2
Weight loss	5.0
Total	13.6

Fixed and variable costs directly associated with solar drying and natural air drying were just about equal to the 10-cent cash discount for No. 3 corn. These costs include:

Item	Cents per bushel
Fixed costs:	
Aeration	1.8
Solar-related	2.5
Subtotal	4.3
Variable costs:	
Aeration	0.6
Solar-related	5.4
Subtotal	6.0
Total costs	10.3

CONCLUSIONS

Results of the FALDRY simulation model show that supplemental-solar drying is neither necessary nor successful every year in the west central Great Plains. A comparison of drying costs and cash premiums for high-quality corn suggests that even if solar-supplemented heat could be used successfully every year, farmers would not be economically rewarded for their efforts. Costs of solar-supplemented drying exceeded the prorated economic losses due to corn deterioration. This finding suggests the possibility that farmers may market lower quality corn if fuel shortages cause them to use low-temperature solar or natural air drying methods and if they are not economically rewarded for producing No. 2 grade corn.

Since results of the study showed that corn deteriorated even with solar-supplemented heat in poor drying years, it may also be concluded that high-speed, high-temperature drying is necessary to avoid field losses and ensure the marketing of high-quality corn.

Previous studies throughout the Corn Belt have shown that solar collectors are not a reliable source of energy for drying grain every year. The probability of successful solar drying is higher in the Dodge City area than in the Corn Belt. Therefore, the results of this economic analysis are assumed to be reasonably accurate for corn-producing areas. Also, the minimal economies associated with the solar drying function suggest that the economics of using a solar-supplemented system would be about the same for larger systems.

CONCLUSIONS

Further research is needed on the use of solar collectors to supplement natural air drying of batch-in-bin systems with more shallow depths of grain and larger diameter bins.

REFERENCES

(1) Behlen Manufacturing Company. Modern Grain Conditioning. 2nd ed. Columbus, Nebr. (undated).

(2) Circle Steel Corporation. Bin Drying, Batch, Layer, Stir, Electric. Taylorville, Ill. Jan. 1975.

(3) Converse, Harry H. "Update on Solar Grain Drying." Mimeograph summary of talk presented at the Mid-Central Regional Meeting of the American Society of Agricultural Engineers (ASAE), St. Joseph, Mo. Apr. 8, 1978.

(4) Dick, C.L., Jr., and C.R. Grebensteub. "Economies of Scale in the Acquisition of Solar Energy." Paper presented at Systems Simulation and Economic Analysis Conference Proceedings, Conference 800101, Bahia Hotel, San Diego, Calif. Sponsored by Systems Development Division, Office of Solar Applications, U.S. Dept. Energy. Jan. 23-25, 1980.

(5) Frederick, A.L. (Roy). Selling Kansas Feed Grains Wet or Dry. C 503. Coop. Ext. Serv., Kansas State Univ., Manhattan, Kans. May 1974.

(6) Heid, Walter G., Jr. Kansas Grain Dryer Inventory. Contribution No. 80-403-D. Dept. of Econ., Kansas Agri. Exp. Sta., Manhattan, Kans. July 1980.

(7) __________. Solar Assisted Combination Grain Drying: An Economic Evaluation. AER-453. U.S. Dept. Agr., Econ., Stat., Coop. Serv. Feb. 1980.

(8) __________. The Performance and Economic Feasibility of Solar Grain Drying Systems. AER-396. U.S. Dept. Agr., Econ., Stat., Coop. Serv. Feb. 1978.

(9) __________. The Young Solar Collector: An Evaluation of Its Multiple Farm Uses. AER-466. U.S. Dept. Agr., Econ., Stat., Coop. Serv. May 1981.

(10) Linville, Randal L. "The Economics of Farm Grain Storage and Drying in Kansas." Unpublished M.S. thesis. Dept. Agr. Econ., Kansas State Univ., Manhattan, Kans. 1978.

(11) Midwest Plan Service. Low Temperature and Solar Grain Drying Handbook. MWPS-22. Iowa State Univ., Ames, Iowa. 1980.

(12) Pierce, R.D., and T.L. Thompson. "Solar Grain Drying in the North Central Region--Simulation Results." ASAE paper No. 76-3517. Paper presented at the ASAE winter meeting, Chicago, Ill. Dec. 1976.

(13) Sauer, D.B., and R. Burroughs. "Fungal Growth, Aflatoxin Production, and Moisture Equilibration in Mixtures of Wet and Dry Corn." Phytopathology, Vol. 70, No. 6, pp. 516-521. American Phytopathology Society. 1980.

(14) Saul, R.S., and J.L. Steele. "Why Damaged Shelled Corn Costs More to Dry." Agricultural Engineering 27:(6)326-329, 337. June 1966.

(15) SOLMET data (revised). "Availability of Direct, Total, and Diffuse Solar Radiation for Fixed and Tracking Collectors in the USA. Sand 77-0885. Jan. 30, 1978.

(16) Uhrig, J.W., and J.L. Strom. "Economics of Drying Corn." EC-390. Coop. Ext. Serv., Purdue Univ., West Lafayette, Ind. Feb. 1970.

(17) U.S. Department of Agriculture, Federal Grain Inspection Service. The Official United States Standards for Grain. Jan. 1978.

(18) Van Ee, G.R., and G.L. Kline. "FALDRY--A Model for Low-Temperature Corn Drying Systems." ASAE paper No. 79-3524. Paper presented at the ASAE winter meeting, New Orleans, La. Dec. 1979.

Appendix table 1--Days required to dry top layer of corn to 15.5-percent moisture, average grain temperature, and accumulated deterioration of the top layer 1/

Year	Temp. rise 2.7 degrees (F)			Temp. rise 5.7 degrees (F)			Temp. rise 8.7 degrees (F)		
	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration
	No.	Degrees F	Percent	No.	Degrees F	Percent	No.	Degrees F	Percent
1955	25	64	1.681	22	57	1.502	19	78	1.281
1956	14	66	.379	12	76	.393	12	78	.510
1957	21	72	.777	19	74	.753	18	74	.736
1958	22	70	.940	20	70	.933	19	70	.989
1959	25	54	1.010	21	60	.981	18	57	.997
1960	22	61	1.123	20	68	1.065	18	60	1.006
1961	22	68	.574	21	67	.603	19	66	.623
1962	30	61	2.654	26	71	2.174	22	68	1.597
1963	21	72	1.379	19	73	1.377	18	76	1.392
1964	25	57	.947	23	58	.988	21	60	1.049
1965	30	70	1.150	26	70	1.136	24	68	1.066
1966	25	63	.980	22	67	.943	20	62	.949
1967	20	74	.877	19	77	.826	17	74	.796
1968	18	63	.756	17	75	.785	16	77	.735
1969	24	64	2.183	21	60	1.944	20	80	1.845
1970	25	43	1.286	22	73	1.147	20	74	1.202
1971	24	59	.772	21	65	.770	19	63	.735
1972	20	66	.839	18	69	.842	16	63	.858
1973	27	52	1.416	25	77	1.272	22	70	1.236
1974	23	55	.907	21	74	.817	19	73	.817

1/ Assumes September 15 harvest date, 25-percent-moisture corn, and 5-hp fan.

Appendix table 2--Days required to dry top layer of corn to 15.5-percent moisture, average grain temperature, and accumulated deterioration of the top layer 1/

Year	Temp. rise 2.7 degrees (F)			Temp. rise 5.7 degrees (F)			Temp. rise 8.7 degrees (F)		
	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration
	No.	Degrees F	Percent	No.	Degrees F	Percent	No.	Degrees F	Percent
1955	19	71	0.428	16	65	0.460	14	75	0.456
1956	12	72	.219	11	73	.227	11	76	.237
1957	19	69	.394	17	71	.383	16	74	.372
1958	20	64	.508	18	57	.530	16	58	.530
1959	18	52	.497	16	53	.496	14	66	.496
1960	18	64	.454	16	60	.434	14	72	.419
1961	20	60	.328	18	56	.334	15	75	.329
1962	27	68	.941	23	66	.823	19	65	.765
1963	19	70	.725	17	70	.731	16	68	.742
1964	23	61	.538	20	56	.546	18	63	.516
1965	27	56	.548	23	65	.509	21	66	.462
1966	22	65	.486	19	64	.487	17	61	.481
1967	18	72	.420	16	71	.418	14	61	.420
1968	16	71	.383	15	71	.395	14	75	.378
1969	21	57	.852	19	78	.786	17	75	.353
1970	22	71	.602	20	71	.579	18	70	.557
1971	21	62	.377	19	60	.347	17	78	.315
1972	17	63	.423	15	57	.431	14	69	.429
1973	25	74	.600	21	59	.559	19	68	.526
1974	21	72	.418	18	62	.417	17	66	.425

1/ Assumes September 15 harvest date, 23-percent-moisture corn, and 5-hp fan.

Appendix table 3--Days required to dry top layer of corn to 15.5-percent moisture, average grain temperature, and accumulated deterioration of the top layer 1/

Year	Temp. rise 2.7 degrees (F)			Temp. rise 5.7 degrees (F)			Temp. rise 8.7 degrees (F)		
	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration
	No.	Degrees F	Percent	No.	Degrees F	Percent	No.	Degrees F	Percent
1955	19	40	0.233	18	50	0.252	16	53	0.274
1956	24	45	.451	21	45	.475	19	51	.475
1957	39	46	.504	31	49	.442	26	48	.439
1958	20	51	.239	18	50	.255	16	49	.269
1959	28	43	.368	23	33	.375	20	65	.373
1960	32	50	.484	27	38	.500	23	49	.535
1961	23	34	.282	10	48	.279	18	67	.277
1962	25	43	.330	22	44	.347	19	51	.343
1963	26	56	.899	23	55	.918	20	56	.960
1964	28	54	.538	22	54	.490	20	63	.460
1965	29	48	.693	25	54	.662	21	56	.660
1966	24	55	.204	22	45	.217	19	38	.227
1967	19	43	.173	18	52	.184	16	51	.196
1968	24	41	.336	21	56	.345	19	60	.345
1969	37	44	.481	31	36	.485	28	57	.464
1970	35	46	.359	29	44	.363	26	53	.367
1971	30	56	.543	26	47	.575	23	41	.612
1972	31	46	.347	27	47	.297	24	53	.295
1973	20	42	.315	18	57	.337	17	55	.362
1974	33	44	.757	27	51	.747	22	63	.761

1/ Assumes October 15 harvest date, 25-percent-moisture corn, and 5-hp fan.

Appendix table 4--Days required to dry average moisture content of corn to 15.5 percent, average grain temperature, and accumulated deterioration of top layer 1/

Year	Temp. rise 2.7 degrees (F)			Temp. rise 5.7 degrees (F)			Temp. rise 8.7 degrees (F)		
	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration
	No.	Degrees F	Percent	No.	Degrees F	Percent	No.	Degrees F	Percent
1955	20	70	0.625	15	62	0.496	13	73	0.464
1956	8	61	.154	7	65	.154	7	67	.163
1957	15	65	.307	13	65	.284	11	66	.260
1958	16	48	.482	14	65	.475	12	58	.448
1959	18	51	.470	13	60	.445	11	65	.418
1960	16	62	.434	14	66	.411	13	66	.373
1961	16	50	.278	15	55	.286	13	60	.268
1962	23	64	.909	19	65	.749	15	63	.615
1963	15	59	.657	13	63	.634	12	67	.617
1964	19	51	.531	17	57	.507	15	70	.475
1965	24	60	.558	20	62	.474	18	63	.438
1966	18	62	.461	16	55	.438	14	67	.413
1967	14	53	.351	12	64	.344	10	64	.306
1968	12	62	.300	11	64	.300	10	65	.287
1969	17	66	.805	16	71	.746	14	73	.672
1970	18	61	.573	16	65	.524	14	62	.512
1971	18	59	.295	15	74	.226	13	70	.184
1972	14	61	.392	11	67	.356	10	70	.341
1973	21	54	.554	19	63	.519	16	62	.450
1974	16	55	.386	15	62	.385	13	66	.374

1/ Assumes September 15 harvest date, 25-percent-moisture corn, and 5-hp fan.

Appendix table 5--Days required to dry average moisture content of corn to 15.5 percent, average grain temperature, and accumulated deterioration of top layer 1/

Year	Temp. rise 2.7 degrees (F)			Temp. rise 5.7 degrees (F)			Temp. rise 8.7 degrees (F)		
	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration	Days required	Grain temperature	Deterioration
	No.	Degrees F	Percent	No.	Degrees F	Percent	No.	Degrees F	Percent
1955	9	60	0.354	8	73	0.351	7	72	0.321
1956	6	65	.144	6	68	.156	5	65	.142
1957	12	62	.257	11	62	.258	10	64	.256
1958	13	54	.434	11	61	.423	10	74	.414
1959	11	64	.409	9	69	.346	8	71	.322
1960	12	62	.370	10	65	.341	7	71	.250
1961	14	56	.266	11	53	.241	10	56	.249
1962	20	63	.769	16	61	.697	13	67	.590
1963	13	63	.617	12	66	.625	10	71	.571
1964	18	55	.503	14	56	.398	12	63	.394
1965	22	57	.497	18	61	.433	15	64	.397
1966	15	62	.412	13	61	.382	11	68	.335
1967	11	69	.338	9	63	.297	8	67	.288
1968	10	61	.291	9	70	.298	8	78	.261
1969	15	69	.626	14	71	.618	12	72	.548
1970	16	63	.478	14	60	.453	12	54	.443
1971	15	72	.270	13	68	.210	12	69	.233
1972	10	66	.310	9	63	.300	8	59	.296
1973	19	61	.539	15	58	.435	12	65	.394
1974	14	54	.344	12	65	.329	12	68	.321

1/ Assumes September 15 harvest date, 23-percent-moisture corn, and 5-hp fan.

Appendix table 6--Days required to dry average moisture content of corn to 15.5 percent, average grain temperature, and accumulated deterioration of top layer 1/

Year	Temp. rise 2.7 degrees (F)			Temp. rise 5.7 degrees (F)			Temp. rise 8.7 degrees (F)		
	Days required	Grain temperature	Deteri-oration	Days required	Grain temperature	Deteri-oration	Days required	Grain temperature	Deteri-oration
	No.	Degrees F	Percent	No.	Degrees F	Percent	No.	Degrees F	Percent
1955	12	54	0.191	11	53	0.200	10	51	0.211
1956	16	51	.397	13	55	.334	12	54	.345
1957	33	40	.441	23	46	.408	18	62	.383
1958	11	49	.188	13	51	.184	9	53	.204
1959	19	53	.321	14	51	.273	12	46	.281
1960	24	45	.449	19	50	.436	17	49	.461
1961	13	57	.181	11	46	.172	10	54	.183
1962	17	51	.289	14	52	.282	13	63	.284
1963	19	46	.812	16	58	.832	14	52	.836
1964	19	63	.461	16	63	.379	13	63	.293
1965	20	55	.550	17	54	.528	15	60	.517
1966	15	47	.161	13	58	.150	12	58	.147
1967	11	48	.132	10	50	.139	9	61	.142
1968	16	59	.263	15	57	.272	13	51	.269
1969	29	50	.443	25	53	.425	22	54	.404
1970	26	45	.323	23	51	.316	18	44	.313
1971	23	34	.512	19	46	.535	15	43	.533
1972	24	45	.273	21	53	.258	17	38	.253
1973	12	54	.263	11	56	.275	10	59	.286
1974	28	43	.748	18	54	.667	15	63	.599

1/ Assumes October 15 harvest date, 25-percent-moisture corn, and 5-hp fan.

☆ U. S. GOVERNMENT PRINTING OFFICE : 1981 720-003/3723

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D.C. 20250

Economics and Statistics Service

The Economics and Statistics Service (ESS) collects data and carries out research on food and agriculture, international agricultural trade, natural resources, and rural development. The Economics unit researches and analyzes production and marketing of major commodities; foreign agriculture and trade; economic use, conservation, and development of natural resources; trends in rural population, employment, and housing and rural economic adjustment problems; and performance of agricultural industry. The Statistics unit collects data on crops, livestock, prices, and labor, and publishes official USDA State and national estimates through the Crop Reporting Board. Through its information program, ESS provides objective and timely economic and statistical information for farmers, government policymakers, consumers, agribusiness firms, cooperatives, rural residents, and other interested citizens.