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ENERGY CONSERVATION IN GRAIN (CORN) DRYING WITH
COMBINATION HIGH-TEMPERATURE, LOW-TEMPERATURE
METHODS

Final Report for the Period July 1, 1978–September 30, 1980

By
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Bills-135
NTIS-25

January 1981

Work Performed Under Contract No. AS02-78CS40060

University of Minnesota
Agricultural Experiment Station
St. Paul, Minnesota

U. S. DEPARTMENT OF ENERGY

Division of Industrial Energy Conservation

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Prepared for
THE U.S. DEPARTMENT OF ENERGY
AGREEMENT NO. DE-AC02-78CS40060.M002

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ABSTRACT

Field drying experiments were carried out during the 1975 through 1978 harvest seasons at the University of Minnesota Rosemount Experiment Station. Several combination drying experiments were conducted each season along with a control (conventional drying) experiment. Based on the results of the field experiments, comparisons of energy requirements for combination and conventional drying were made.

Performance of the low-temperature, in-storage phase of combination drying was evaluated using computer simulation. Drying performance using ambient air was compared to performance when small amounts of supplemental heat were added, either solar or constant source heat. Long term weather records were used to evaluate variations in performance from year to year.

The following conclusions can be drawn based on the results of the field experiments and simulation analyses:

1. Combination drying significantly reduces propane or natural gas fuel requirements with an increase in electrical energy for drying.
2. Total energy equivalent of propane or natural gas, and electricity as metered on the farm is reduced with combination drying.
3. High-speed dryer capacity is also significantly increased with combination drying. Grain quality is also improved.
4. Addition of supplemental heat to the in-storage phase of drying provides a modest increase in drying reliability and some reduction in fan energy requirements.
5. Supplemental heat for in-storage drying from a fossil-fuel-derived source increases the total energy input for drying as compared to ambient-air drying.
6. Energy cost savings exist for combination drying at most levels of fuel cost. Investment costs for equipment modifications, which vary significantly from situation to situation, will determine whether it is feasible to adopt combination drying. An example economic analysis showed favorable rates of return for combination drying over a wide range of conditions.
7. Currently, the factors that may provide the greatest incentives to shift to combination drying include: 1) increased drying capacity, and 2) increased flexibility of energy source (propane or electric).

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ENERGY CONSERVATION IN GRAIN (CORN) DRYING WITH COMBINATION HIGH-TEMPERATURE, LOW-TEMPERATURE METHODS

by

R. Vance Morey, Robert J. Gustafson,
Harold A. Cloud, and Kenneth L. Walter

INTRODUCTION

Existing (conventional) drying systems rely on heat energy, usually supplied by propane for on-farm systems to remove moisture. Typical farm type dryers are illustrated in Figure 1. These high-temperature dryers operate with a drying air temperature from 120 to 240°F. Grain is cooled in the dryer before being discharged to storage. The drying and cooling cycle times normally range from 2 to 24 hours.

The need to reduce energy use, particularly propane, has led to efforts to improve efficiency of grain drying systems. Combination high-temperature, low-temperature drying offers potential for meeting this need. Combination drying is any system in which high-temperature drying is followed by in-storage cooling and low-temperature drying (Figure 2). The high-temperature phase can be a continuous flow or automatic batch dryer, or a bin dryer as illustrated in Figure 1. The purpose of the high-temperature dryer is to reduce corn moisture content to a level where drying can be safely completed with in-storage, low-temperature methods. In-storage drying is accomplished by moving low-temperature air through the grain mass. This process may take from four to eight weeks, or longer to complete. In fact, drying may be halted in late fall and completed during the following spring.

The bin is equipped with a full perforated drying floor and a fan delivers 1 to 1.25 cubic feet of air per minute per bushel of grain (cfm/bu) through the full bin. These airflows can be delivered to bins of convenient depths with reasonable fan horsepower requirements as indicated in Table 1. Small amounts of supplemental heat (enough to raise the temperature of the air 2-5°F) are sometimes added although they usually are not necessary.

Potential advantages of the combination approach compared to conventional drying with in-dryer cooling include: a) reduced energy requirements, b) increased drying capacity, and c) improved grain quality.

Figure 1. Schematic diagrams of high-temperature drying systems.

COMBINATION DRYING

Figure 2. Schematic diagram of combination drying system.

Table 1. Brake horsepower per 10,000 bushels of corn for several air-flow and depth combinations. ^{1/}

Airflow rate, cfm/bu	Depth of corn, ft.						
	10	12	14	16	18	20	22
0.75	1.3	1.9	2.8	3.7	5.0	6.3	7.6
1.0	2.5	3.8	5.4	7.4	9.9	12.6	16.1
1.25	4.1	6.3	9.3	12.6	16.5	21.7	28.0
1.50	6.1	9.5	14.2	18.9	25.8	33.1	41.6

^{1/} Calculated horsepower per 10,000 bushels of corn based on static pressure of 1.5 x ASAE D272 (Anon, 1979) and a fan efficiency of 50%.

Propane or natural gas requirements for high-temperature drying are reduced since less moisture is removed in the high-temperature phase. The amount of savings depends on the moisture content level at which grain is discharged from the high-temperature dryer and the efficiency of the dryer. For example, the efficiency of heated air dryers depends on the airflow rate (cfm/bu), drying air temperature, and initial moisture content.

Electrical energy requirements are increased due to the fan energy for low-temperature drying. However, total energy requirements are reduced and the additional electrical energy will be used in the months of October and November and possibly March, April, and early May of the following spring, which are between the seasonal air conditioning and heated peaks for the utility system.

Drying capacity of the high-speed system is significantly increased since less moisture is removed in the high-temperature dryer. Cooling in the storage bin provides additional capacity for the high-temperature dryer. If the high-temperature dryer is a batch process, the cooling cycle can be eliminated. If the high-temperature dryer is a continuous-flow process, the cooling section of the dryer can be equipped with a propane burner to

provide additional capacity. Capacity increases of 200 to 300 percent for the high-temperature dryer are possible.

Combination drying leads to improved grain quality since grain is discharged at higher moisture contents from the high-temperature dryer and cooling is often delayed. This results in reduced susceptibility to breakage in future handling. Test weight increase can be another favorable quality characteristic.

This report summarizes combination drying studies from four corn harvest seasons (1975-1978) at the University of Minnesota Rosemount Experiment Station. The report also includes results of simulation analysis of the low-temperature phase of combination drying. The model used for this analysis was validated with experimental data from the field studies. Finally, design and management recommendations, and economic considerations for combination drying are discussed.

EXPERIMENTAL WORK

Equipment and Procedures

Field drying experiments were carried out at the University of Minnesota Rosemount Experiment Station which is located approximately 25 miles southeast of Minneapolis-St. Paul. This Station produces approximately 60,000 bushels of corn annually and is equipped with a centralized drying system including a 300 bushel automatic batch dryer, a 300 bu/hr vertical elevator and 50,000 bushels of storage.

The automatic batch dryer has a column width of one foot and an airflow rate of approximately 70 cfm/bu. Grain passes through a two-stage gravity screener as it is discharged from the dryer.

Identical 3000 bushel bins equipped with drying floors and 1.5 hp axial flow fans are used in combination drying experiments. The bins are 18 feet in diameter with an approximate depth of 14.5 feet from the drying floor to the eave. The fans deliver approximately 1 cfm/bu airflow when the bins are filled. Corn from conventional high-temperature drying experiments also is stored in 3000 bushel bins with aeration at approximately 0.1 cfm/bu.

Drying fans in the high-temperature system and low-temperature drying bins were metered individually to obtain electrical energy input. Propane input to the high-temperature dryer was measured with a gas meter. Temperatures

were recorded hourly at various points in the low-temperature bins and bin plenums, and at two-minute intervals in the high-temperature dryer when it was operating.

Relative humidity of the ambient air was measured hourly with a Dunmore-type sensor. Airflows were determined by taking a traverse with a pitot tube in air-measuring ducts ahead of the low-temperature drying fans.

A slotted tube sampler was used to obtain samples as grain was loaded into the high-temperature dryer and after screening as the dryer was unloaded. Each bin was sampled after cooling had been completed and then periodically throughout the remainder of the ambient-air drying tests with a vacuum probe. Moisture contents were determined by oven drying at 103°C for 72 hours.

Experiments

A total of ten combination drying experiments and four control experiments carried out over the four drying seasons are summarized in Table 2. The combination drying experiments (A, B, C, D, F, H, I, J, L, M) involved initial high-temperature drying at temperatures of from 195 to 287°F. Grain was discharged hot from the dryer, cooled in the bin, and then drying was completed with ambient (unheated) air. The low-temperature phase of combination drying started at moisture contents ranging from 18 to 23 percent with most tests starting at between 21.5 to 22.5 percent. Low-temperature drying during the fall lasted from 30 to 60 days depending on conditions. For some of the bins, additional drying was carried out in the spring.

The control experiments (E, G, K, N) involved conventional high-temperature drying with in-dryer cooling. Drying air temperatures ranged from 194 to 216°F. The bins were filled on a range of dates over the four harvest seasons reflecting the variability in corn maturity dates from season to season.

Because of the variability in weather conditions from season to season, results are variable. Favorable field drying conditions in 1975 and 1976 resulted in relatively low moisture contents into the high-temperature dryer. Therefore, less moisture was removed in the high-temperature phase of some tests. Variation in weather conditions throughout the fall had a significant effect on the final fall moisture content that was reached with ambient-air drying. In most cases, if operation was continued into late November or early December, average bin moisture contents were in the 16 to 17 percent range.

For the high-temperature phase of combination drying, the energy requirements range from approximately 1400 to 2100 Btu/lb of water removed. For conventional high-temperature drying with in-dryer cooling, energy requirements range from approximately 2400 to 2900 Btu/lb.

Electrical energy requirements for in-storage drying in the fall also were quite variable ranging from 514 to 829 Btu/lb of water removed. This large range results from varying weather conditions from year to year. The highest

Table 2. Summary of performance of combination and conventional drying treatments at the Rosemount Experiment Station (1975-1978).

Test Identification	1975				1976			1977				1978		
	Combination ^{1/}				Cont. ^{2/}	Comb.	Cont.	Combination		Cont.	Combination		Cont.	
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
In-Storage Drying Starting Date	10/16	10/15	10/10	10/13	10/17	10/1	10/6	9/21	9/22	10/3	10/15	10/9	10/9	10/16
Days of Fall Operation	29	41	53	50	--	56	--	56	58	47	--	53	53	--
Bushels at 15.5%	2943	2831	2710	2636	3092	2643	1385	2741	2739	2680	3228	2814	2836	3067
Moisture Contents, % w.b.														
Into HT Dryer	23.0	23.1	25.6	27.0	22.3	26.3	19.2	27.3	28.7	27.2	24.0	30.5	28.4	26.8
In Storage After Cooling	18.0	20.0	22.2	22.8	15.8	22.4	15.9	21.6	21.0	20.6	16.3	22.7	22.3	15.9
At Fan Shut-Off in Fall	14.5	16.0	16.6	17.3	--	14.5	--	16.7	16.6	16.7	--	16.5	16.5	--
After Spring Operation	--	12.6	--	12.9	--	13.1	--	13.8	13.7	13.0	--	14.6	14.5	--
Energy, Btu/lb water														
Prop. (High-Temp Dryer)	1948	1915	1428	1625	2416	1460	2847	2014	1877	2109	2526	1797	1681	2859
Elec. (High-Temp Dryer)	27	29	23	22	45	29	57	29	25	23	42	29	29	47
Elec. (Storage-Fall)	514	618	636	561	--	421	--	657	829	751	--	533	559	--
Elec. (Storage-Spring)	--	511	--	395	--	397	--	1143	1341	982	--	1144	1045	--
Total ^{3/}	1409	1011	977	882	2461	757	2904	1381	1515	1510	2568	1294	1174	2906
Temperatures, °F														
High Temp., Drying Air	214	214	211	253	216	220	197	205	206	287	215	195	199	194
Ambient	52	42	46	68	53	60	42	58	59	60	50	59	64	57
Grain Out	132	113	110	125	--	110	--	122	129	147	--	125	118	--
In Storage ^{4/} , Drying Air	46	42	40	40	--	38	--	48	47	45	--	38	38	--
(Fall) Dew Point	35	33	32	31	--	23	--	39	38	36	--	27	27	--

^{1/} Combination drying--High-temperature drying followed by in-storage cooling and ambient-air drying.

^{2/} Control-conventional high-temperature drying with in-dryer cooling.

^{3/} Energy equivalent per lb of water removed over entire moisture content range including propane and electrical energy as metered on the farm. Includes spring operation where indicated.

^{4/} Average temperature during fall drying period.

energy requirements for fall in-storage drying occurred during the 1977 season which was characterized by wet and humid conditions.

Drying air temperatures for the high-temperature dryer and the fall in-storage drying are summarized at the bottom of Table 2.

More detailed results of spring drying performance are presented in Table 3. Energy requirements for spring drying are highly variable. They were particularly high for the 1977 (Spring, 1978) and 1979 (Spring, 1979) tests because of the unfavorable weather conditions encountered during these drying periods.

To better compare and summarize the results of the tests, the combination and conventional drying systems are compared over identical moisture content ranges by using energy estimates based on the tests in Table 2. These results, presented in Table 4, provide an indication of total energy used to dry a bushel of grain for the moisture content ranges indicated. Combination drying leads to substantial reductions in energy supplied by propane or an equivalent fossil fuel to provide heat energy. Although electrical energy increases are significant with combination drying, substantial total (propane plus electric) energy savings exist. The results also show the effect of changing to the in-storage drying phase at 21.5 percent moisture content versus 20 percent moisture content.

Supplemental Heat Comparisons

One bin was equipped with an electric resistance heater to study the effect of supplemental heat on low-temperature drying performance. Tests were run in 1975, 1977, and 1978. Because of limited availability of wet corn during the 1976 season no test was run. These results are summarized in Table 5.

For the 1975 season, the fan and heater were operated only during the off-peak hours of 9 p.m. to 9 a.m. each day. A 3 hp fan delivered an airflow of approximately 2 cfm/bu to the 2200 bushels of grain during the 12-hour period of operation. This provided a daily total airflow comparable to the ambient air bins equipped with fans delivering approximately 1 cfm/bu over a 24-hour period. Eight kW of electric heat was applied to the approximately 4400 cfm airflow. For low-temperature drying under this operating procedure, the fan energy requirement was 719 Btu/lb of water with an additional 1768 Btu/lb for the electric heater or a total of 2487 Btu/lb. This value is much higher than the comparable values for 1975 ambient-air drying in Table 2. (Tests A-D). This is due to the fact that the fan was not operating during the period of the day (9 a.m. to 9 p.m.) when the drying potential of ambient air is greatest. Also, some deterioration of the grain at the top of the bin was observed, apparently because of high temperatures occurring in the top of the bin on warm sunny days when the fan was not running.

Based on the results of 1975, it was decided to operate the fan 24 hours a day with supplemental heat supplied off-peak from 11 p.m. to 8 a.m. in the 1977 and 1978 tests. An airflow of 1 cfm/bu was supplied for a total flow of approximately 3000 cfm. Eight kW of electric heat was applied during the off-peak period.

Table 3. Summary of spring operation.

	1975 (Spring, 1976)		1976 (Spring, 1977)	1977 ^{4/} (Spring, 1978)			1978 ^{4/} (Spring, 1979)	
	B ^{1/}	D ^{2/}	F ^{3/}	H	I	J	L	M
Fan Start	3/31	3/18	4/7	3/21	3/21	3/21	4/10	4/10
Fan Stop	5/4	4/27	4/22	5/18	5/18	5/11	5/19	5/19
Spring Moist. Cont., % w.b.								
Initial	16.0	17.3	14.5	16.7	16.6	16.7	16.5	16.5
Final	12.6	12.9	13.1	13.8	13.7	13.0	14.6	14.5
Energy, Btu/lb water	511	395	397	1381	1515	1510	1144	1045
Temperature, °F.								
Drying Air	--	--	54	48	48	46	49	49
Dewpoint	--	--	39	37	37	35	35	35

^{1/} Fan ran 8:30 a.m. to 11:30 p.m., 3/31-4/15; ran 24 hours per day, 4/15-5/4.

^{2/} Fan ran 8:30 a.m. to 11:30 p.m., 3/18-4/16; ran 24 hours per day, 4/16-4/27.

^{3/} Fan ran 24 hours per day, 4/7-4/11; off 4/12-4/20; ran 24 hours per day, 4/21-4/22.

^{4/} Fan ran 24 hours per day.

Table 4. Estimated energy requirements for drying a bushel of corn to 15.5% moisture content.^{1/}

Drying Method	Initial Moisture Content, % w.b.			
	25.5%		28.5%	
	Propane Btu(gal) ^{2/}	Electric Btu(kWh) ^{3/}	Propane Btu(gal)	Electric Btu(kWh)
Conventional High-Temp to 15.5% In-Dryer cooling	18798(.205)	338(.10)	25458(.278)	458(.13)
Combination Discharge hot, 21.5% in storage after cooling dry to 15.5% with ambient air	6150(.067)	2870(.84)	11212(.122)	2942(.86)
Combination Discharge hot, 20% in storage after cooling dry to 15.5% with ambient air	8299(.091)	2167(.63)	13361(.149)	2239(.66)

^{1/} The estimates are based on energy requirements from Table 2. For conventional drying energy estimates are: propane = 2500 Btu/lb water; electric = 45 Btu/lb water. For combination drying energy estimates are propane = 1900 Btu/lb water; electric high-temperature dryer = 27 Btu/lb water. Ambient-air drying = 650 Btu/lb water.

^{2/} 1 gallon propane = 91,600 Btu

^{3/} 1 kWh electricity = 3413 Btu

These results (Table 5) show some reduction in fan energy when compared to the 1977 and 1978 ambient-air results of Table 2 (Tests H, I, J, L, M). However, the energy input from the heater (953 Btu/lb in 1977 and 772 Btu/lb in 1978) leads to a total energy input (fan plus heater) which is much larger than the comparable ambient-air results. The additional energy input from the heater resulted in bin moisture contents at fall shut-off which were less than one percentage point less than the comparable ambient-air tests.

These results along with computer simulation results (discussed in a later section) indicate that ambient-air drying results in less energy input for the low-temperature drying phase than supplemental heat drying. From these results, it also appears that off-peak costs for electrical energy need to be much lower than the standard rates to make this an economically attractive alternative.

Grain Quality Results

Field Experiments

Grain quality characteristics associated with each of the drying treatments are included in Table 6. Conditions at the time the bins were emptied provide an indication of how the grain would have been graded. Test weight is influenced by grain variety and growing conditions as well as drying treatment. For example, the wet corn used for test K had a higher than normal test weight as it came from the field; therefore, the test weight after drying was high.

Susceptibility to breakage is an indication of the potential for breakage in future handling (Table 6). Breakage susceptibility was determined with a Stein breakage tester. Samples were slowly conditioned at 80°F dry bulb and 70°F wet bulb temperatures to yield a moisture content of approximately 13 percent for the breakage tests. The percentage increase in breakage susceptibility during drying provides a relative measure of the effect of the drying treatment on quality. In all years, the percentage increase in breakage susceptibility is higher for the conventional drying (control) treatment than for the combination treatments.

Percentage decrease in germination during grain drying is also included in Table 6. Grain with higher germination may be a better storage risk.

High-Speed Dryer--1978

Grain quality changes in the high-speed dryer were evaluated for several batches during the 1978 season. The dryer was set up to allow sampling of the grain at four locations across the 12-inch column from the inside (next to the heated air plenum) to the outside (exhaust). As drying progressed, grain samples were collected across the column. Temperatures also were recorded at several locations across the column.

Samples were analyzed for moisture content, breakage susceptibility and germination. Breakage susceptibility was determined with a Stein breakage tester. Samples were slowly conditioned at 80°F dry bulb and 70°F wet bulb

Table 5. Summary of supplemental heat operation

	<u>Year</u>		
	<u>1975^{1/}</u>	<u>1977^{2/}</u>	<u>1978^{2/}</u>
Filling date	10/14	10/6	10/11
Days of Fall Operation	56	44	51
Bushels at 15.5 percent	2196	2898	2666
Moisture Contents, % w.b.			
Into HT Dryer	25.1	--	29.1
In Storage After Cooling	22.2	21.1	22.9
At Fan Shut-Off in Fall	15.3	16.2	15.7
Energy, Btu/lb of water			
Prop. (High-Temp Dryer)	1556	--	2197
Elec. (High-Temp Dryer)	27	--	23
Elec. (Storage-Fan)	719	528	458
Elec. (Storage-Heater)	1768	953	772
Total ^{3/}	2193	1481	1734
Temperature, °F			
High-Temp, Drying Air	212	--	268
Ambient	58	--	54
Grain Out	112	--	137
In-Storage, Drying Air	40	47	39
(Fall) Ambient	32	--	36
Dewpoint	29	36	26

^{1/} Fan and heater operated off-peak from 9 p.m. to 9 a.m. Eight kW of electric heat applied to approximately 4400 cfm.

^{2/} Fan operated continuously, electric heater operated off-peak from 11 p.m. to 7 a.m. Eight kW of electric heat applied to approximately 3000 cfm.

^{3/} Energy requirements per lb of water removed over entire moisture content range including propane and electrical energy as metered on the farm.

Table 6. Selected grain quality characteristics for the treatments of Table 1.

Test Identification	1975					1976		1977				1978		
	Combination ^{2/}				Cont ^{3/}	Comb.	Cont.	Combination			Cont.	Comb.	Cont.	
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Condition at loadout Moisture content, % w.b.	14.5	12.6	16.6	12.9	15.8	13.1	15.6	13.8	13.7	13.0	16.3	14.6	14.5	15.9
Test Wt., lb/bu	55.9	57.3	55.4	55.4	55.6	55.2	57.0	56.1	55.4	55.0	59.5	57.8	57.4	55.5
^{1/} BCFM	1.0	1.4	0.8	0.8	1.7	0.7	2.2	0.4	0.4	0.5	1.7	1.2	1.4	1.1
Increase in breakage suscepti- bility during drying (according to Stein breakage tester), percentage	2.8	1.2	0.9	1.1	4.1	- 1.8	1.5	2.5	2.0	3.0	7.0	6.7	11.1	16.3
Decrease in germination during drying, percentage	60	34	37	58	63	47	44	63	59	82	80	49	57	69

^{1/}
BCFM - percent broken corn and foreign material.

^{2/}
Combination drying - high-speed drying followed by in-bin cooling and low-temperature drying.

^{3/}
Control - conventional drying with in-dryer cooling.

temperatures to yield a moisture content of approximately 13 percent for the breakage tests.

Results for a typical batch are presented in Figures 3 through 7. The drying air temperature was approximately 200°F. Moisture content versus time is shown in Figure 3. As expected, moisture content decreased rapidly at the inside of the column. The moisture content actually increased for a period at the outer edge of the column. Maximum moisture content differential across the column reached approximately 16 percent with a final differential (at 140 minutes) of approximately 12 percent.

Breakage susceptibility versus time increased rapidly at the inside of the column as grain moisture content decreased and grain temperature increased (Figure 4). Breakage susceptibility increased at successive points across the column as the drying front moved across the column with time. At the end of the 140 minute period, there was a wide variation in breakage susceptibility from the inside to the outside of the column. Breakage susceptibility versus moisture content is plotted in Figure 5. A marked increase in breakage susceptibility occurs between 15 and 20 percent moisture content.

Germination as a function of time is shown in Figure 6. Germination drops rapidly at each location as the drying front moves across the column. As drying takes place at each location, the temperature rises rapidly which destroys the germination. Germination plotted versus moisture content in Figure 7 shows that as soon as the moisture content starts to decrease from the initial level germination drops rapidly to zero. Similar results were obtained for the other batches.

One of the conclusions from these results is that breakage susceptibility remains low when grain is above 18 to 20 percent moisture content. This is why combination drying where grain leaves the high-speed dryer at an average moisture content of 20 to 22 percent leads to a significant decrease in breakage susceptibility and, therefore, improved grain quality compared to conventional drying to 15.5 percent.

Additional grain quality results are presented by Gustafson et al (1978) and Gustafson and Morey (1979).

SIMULATION

Computer simulation can be used to study the performance of the low-temperature phase of drying. Since low-temperature, in-storage drying depends primarily on the drying capacity in ambient air, performance is subject to variations in weather conditions. Computer simulation can be used in conjunction with long-term weather records to analyze the performance of drying systems for a variety of conditions. A computer simulation model of the low-temperature drying process has been developed and partially validated (Morey et al, 1979). Additional validation results are presented. The model also is used to evaluate the effects of supplemental heat.

Validation

Moisture content changes in two bins were monitored during fall, 1978,

Figure 3. Moisture content versus time.

Figure 4. Breakage susceptibility versus time.

Figure 5. Breakage susceptibility versus moisture content.

Figure 6. Germination versus time.

Figure 7. Germination versus moisture content.

low-temperature drying. These results were used in further validation of a computer simulation model of the low-temperature drying process. The model is described in detail by Morey et al (1979).

Drying air conditions were recorded hourly for each of the bins throughout the drying tests. The hourly data (plenum temperature and relative humidity) were used as inputs to the model for simulating moisture changes in the bins. The bins were probed approximately every seven days throughout the duration of the tests. The measured moisture contents at various depths provided a basis for evaluating the ability of the model to predict grain moisture contents.

Conditions for the low-temperature drying tests are summarized in Table 7 for the drying periods. Two airflow rates are shown. One is the measured airflow rate based on a pitot tube traverse in an air measuring duct ahead of the fan (approximately 1.2 cfm/bu). The other is an adjusted airflow rate (1.0 cfm/bu) based on the validation results. The reduced airflow rate caused the computed moisture contents to better match the measured moisture contents. The original airflow caused the computed drying front to move too rapidly through the bin. Air loss due to leakage from the plenum and nonuniform airflow can account for this difference. Airflow tends to be higher at the edges of the bin because of reduced resistance to airflow. The sampling locations were either away from the edge of the bin or near the door where leakage is more likely; therefore, the reduced airflow used in the computations seems appropriate.

An example moisture profile from test M shows a comparison of the computed results and measured results at two locations in the bin (Figure 8). The model adequately predicts the shape and location of the drying front, and the moisture contents above and below the front. Generally, good agreement was obtained on other dates.

The data from all sampling dates were pooled for a regression analysis. The computed moisture content, y , was fit to a linear equation as a function of the measured moisture content, x . If the fit were perfect all points would fall on the line $y = x$. The actual regression results are indicated in Table 3, including R-squared, slope and intercept values. One location was sampled in Test L and two locations in Test M. The high R-squared values indicate good agreement between computed and measured results.

These results agree closely with previous validation work (Morey et al, 1979). Considering the potential sources for error in measuring moisture content, relative humidity and airflow in the field, it appears that the model adequately predicts low-temperature drying performance.

Applications

The effect of adding a small amount of supplemental heat to the ambient air to improve the performance of the in-storage drying phase is a major question. The field results indicate a wide variability in energy use from year to year because of the variability in weather conditions. To better evaluate the effect of supplemental heat, the computer simulation model was used to study performance of in-storage drying systems at three locations. The results

Table 7. Summary of conditions for low-temperature validation tests.

Test Bin	L	M
Drying Period for Validation Comparisons	10/18 - 12/1	10/20 - 12/1
Average Drying Air Temperature, °F	37	36
Average Relative Humidity, %	67	66
Initial Moisture Content Conditions, % w.b.		
Average for Bin	22.6	20.8
Top of Bin	22.6	23.2
Airflow rate, cfm/bu		
Measured	1.17	1.19
Estimated from Validation ^{1/}	1.0	1.0

^{1/} Airflow adjusted based on validation procedure.

Figure 8. Comparison of computed and measured moisture profile.

Table 8. Regression comparisons for computed versus measured moisture content.¹

Test-Bin Location	Number of Points	R ²	Intercept (a)	Slope (b)
L - door	80	0.92	-1.382	1.058
M - center	60	0.92	-2.104	1.105
M - door	60	0.93	-1.205	1.032

^{1/} Results for the regression equation $y = a + bx$; where y is the moisture content computed by the model, x is the measured moisture content, a is the intercept parameter, and b is the slope parameter.

of this analysis are presented in Table 9. From 10 to 16 years of weather data are available to analyze the performance of the systems. In all cases, an airflow rate of 1 cfm/bu is used in the comparisons. A temperature rise over the drying fan of 2°F is assumed in all cases. Comparisons are made for ambient-air drying (i.e., no additional supplemental heat above the 2°F from the fan), solar heat which leads to a temperature rise of approximately 2°F in the fall or supplemental heat resulting in 2°F in the fall from a constant source, either electric resistant heating or a small propane-fired burner.

Dry-matter-decomposition in the top layer of grain in the bin in the second worst year of all years simulated is used as an indication of grain deterioration and mold development. The dry-matter-decomposition estimate is based on the data of Steele et al, (1969). Initial moisture contents used in each location are based on obtaining approximately 0.5 percent dry-matter-decomposition for ambient-air drying in the second worst year. The 0.5 percent level of dry-matter-decomposition has been associated with a loss in corn grade by Saul and Steele (1966). Because of differences in temperature and humidity conditions at each of the three locations, different moisture contents are obtained for the same airflow rate at each location.

The dry-matter-decomposition results indicate that a small amount of supplemental heat provides some reduction in dry-matter-decomposition and, therefore, an improvement in drying reliability. The largest effect occurs at Indianapolis, Indiana. The reduction in dry-matter-decomposition is relatively small at other locations. The results also show that a small amount of supplemental heat reduces the amount of fan operating time.

Energy inputs in Table 9 include the drying fan for ambient air and solar drying cases. The energy input from the supplemental heat collected by solar collectors is not included in this comparison. No additional fan energy is assumed for drawing air through a solar collector. For constant-source supplemental heat, the energy input includes the drying fan and heater. The results show a significant increase in energy for drying when energy from a constant source such as propane or electrical is used for supplemental heat. Some reduction in fossil-fuel derived energy is obtained with the addition of solar energy. However, this reduction is relatively small and probably in most cases does not justify the cost of collectors.

The final column in Table 9 indicates the average bin moisture contents that are obtained when the top of the bin drops below 18 percent. Addition of supplemental heat lowers the average moisture content in the bin compared to ambient-air drying. However, in some cases this may result in overdrying of the bottom of the bin in order to complete drying at the top of the bin.

DESIGN AND MANAGEMENT

This section discusses management recommendations for combination drying. These include the moisture content levels at which the switch can be made from the high-temperature phase to the low-temperature phase, recommendations for management during the harvesting and storage period, and discussion of flexibility available with a drying bin.

Table 9. Effect of supplemental heat on drying performance at three locations for 1cfm/bu airflow rate^{1/}

Location	Supplemental Heat	Temperature ^{2/} Rise From Supplemental Heat, °F	Dry-Matter ^{3/} Decomposition, Percent	Fan ^{4/} Operating Days	Total ^{5/} Energy Input, kWh/bu	Ave. ^{6/} M.C. at 18% Top
St. Cloud, MN (21.5% initial M.C.)	Ambient	0.0	0.50	63	1.00	15.4
	Solar Heat	1.6	0.47	50	0.78	15.2
	Constant Source	2.0	0.47	48	1.50	15.1
Des Moines, IA (21.1% initial M.C.)	Ambient	0.0	0.54	42	0.67	14.9
	Solar Heat	2.2	0.46	35	0.55	14.3
	Constant Source	2.0	0.48	35	1.12	14.2
Indianapolis, IN (20.7% initial M.C.)	Ambient	0.0	0.48	56	0.88	15.1
	Solar Heat	2.2	0.38	38	0.59	14.7
	Constant Source	2.0	0.39	38	1.21	14.7

^{1/} Based on computer simulation of performance for 16, 10 and 14 years of weather data at St. Cloud, Des Moines and Indianapolis, respectively. October 16 harvest date.

^{2/} Temperature rise over drying fan is 2°F in all cases. Temperature rise from solar heat is based on a Solar Collector Coefficient of 10°F as defined by Pierce and Thompson (1976).

^{3/} Dry-matter-decomposition in second-worst year based on data of Steele et al. (1969) provides an indication of quality deterioration due to mold growth.

^{4/} Fan operation time to reach bin average moisture content less than 15.5% with the maximum less than 18%.

^{5/} Energy input to drying fan for ambient-air and solar cases. Energy input for fan and supplemental heater for constant source case. Additional energy required to move air through the solar collector is neglected.

^{6/} Actual average bin moisture content when the top drops below 18%.

Moisture Contents

The computer simulation model is used to determine the maximum moisture contents that can be safely dried based on the 0.5 percent dry-matter-decomposition criterion for 1 and 1.25 cfm/bu airflow rates. The values are indicated in Table 10 for St. Cloud, Minnesota, Des Moines, Iowa, and Indianapolis, Indiana. A range of moisture contents is shown for each condition. The lower values should be used early in the season (around October 1) because higher temperatures speed grain deterioration. Initial moisture contents that can be safely handled are lower at Indianapolis than the other locations because of a combination of higher ambient temperatures and humidities.

The moisture content recommendations in Table 10 are for a situation where the bin is filled rapidly over a period of at most several days. If filling can be uniformly spread over a period of two weeks or more, the initial moisture contents that can be safely handled are increased by 1 to 1.5 percentage points.

Management of the System

Harvest Time

It is important not to exceed suggested moisture content levels for discharge from the high-speed dryer to the bin for cooling and drying. During the first year, the moisture content should be reduced a little farther in the high-speed dryer until experience is gained with the system including measuring the moisture content of the warm, moist grain. Since the moisture content of warm grain is difficult to measure accurately, grain samples for controlling the dryer should be taken from the cooled grain in the bin for best results. At these airflows, grain will normally be cooled within one hour after it reaches the bin.

In-storage drying fans should be started as soon as hot corn is delivered to the bin. This will avoid undesirable condensation buildup along the walls of the bin. During in-bin cooling, the hot moist air being discharged will form condensation on the roof and caves of the bin. Condensation should not pose a problem unless water happens to collect and run along roof supports where it is deposited in one place. The downspout to the bin may be a potential source for problems since moist air rising in the downspout will cool with the water condensing and running back into the bin. One solution is to close off the entrance to the downspout at the bin so that air does not travel up the spout. Spring-loaded covers are available which automatically close when corn is not flowing.

In-Storage Drying Period

Experience has shown that the best procedure is to operate the fan continuously until the drying front has moved through the top of the bin. Do not shut the fan off in the fall in periods of rainy weather or high humidity. Fan operation during these periods will continue to move the drying front

Table 10. Maximum initial moisture contents for rapid filling.^{1/}

Airflow, cfm/bu	Location ^{2/}		
	St. Cloud, MN	Des Moines, IA	Indianapolis, IN
1	21 - 21.5 ^{3/}	20.5 - 21.5	20 - 20.5
1.25	21.5 - 22	21 - 22	20.5 - 21

^{1/} Rapid filling - filling the bin over a period of, at most, several days.

^{2/} Based on simulation analysis of drying performance at each location.

^{3/} Lower values in range of moisture contents at each location should be used early in the season (around October 1) because higher temperatures speed deterioration rates.

through the bin and air movement will control heating of the grain. In late fall or early winter, the fan can be shut off according to the guidelines in Table 11. These guidelines are based on analysis of drying performance with weather records from the three locations (St. Cloud, Des Moines, and Indianapolis). After turning the fan off, a cover should be placed over the drying fan to avoid natural air currents through the bin.

Table 11 provides general guidelines for shutting off the fan in the winter and restarting in the spring. Specific weather conditions influence these recommendations. In general, keep the fan running as long as average temperatures are above 25°F. When the temperature drops below these levels for significant periods of time, the fan can be shut off before the indicated dates. Drying proceeds slowly below 25°F; and, more importantly, as long as the grain is below 25°F deterioration rates will be low, even at higher moisture contents.

Storage Period

During the winter, check the top two or three feet of the bin periodically for moisture buildup (particularly near the center) or an increase in grain temperature. Run the fan for a total of six to eight hours every several weeks if the ambient temperature is between 20° and 30°F. This is particularly important following an extended period below 0 to 10°F.

In the spring, if it is necessary to continue drying, start the fan and run continuously according to the schedule in Table 11. If drying in the spring is not necessary, warm up the grain according to normal storage management procedures. At 1 cfm/bu, a warming (or cooling) front can be moved through the bin in 12 to 24 hours; at 1/2 cfm/bu, in 24 to 48 hours. Check the grain temperature at the top of the bin to determine when warm-up has been completed.

If problems are encountered and grain appears to be heating or going out of conditions, move enough to stabilize the situation. This grain can be run through the high-speed dryer to quickly reduce the moisture content to a safe level.

If a portion of the grain is above 15.5 percent when it is time to market (e.g., 17 to 18 percent at the top of the bin), it may be feasible to remove several percentage points in the high-speed dryer before selling. The moisture discount schedule will determine whether this is necessary or economically desirable. Blending of wetter grain with drier grain at the time of sale is another method of reaching the 15.5 percent level.

Grain Handling, Cleaning and Leveling

If a conventional drying system is converted to combination drying, make sure that materials handling between the high-speed dryer and the drying-storage bin does not create a bottleneck. Capacities of augers handling hot, 20 to 22 percent corn will be reduced compared to dry, cooled corn.

Table 11. Recommendations for shutting off the fan in the fall and starting in the spring.^{1/}

Fall Shut-Off (sample grain periodically)^{2/}

- a) Turn off fan when grain in the top of the bin drops below 15½% and temperature of the grain in the top drops below 35°F.
- b) After November 1, if the grain at the top drops below 17%, turn off the fan as soon as the grain temperature at the top drops below 30°F.
- c) After November 15, if the grain at the top drops below 18%, turn off the fan when the grain temperature at the top drops below 30°F.
- d) After December 1, if the grain at the top drops below 19%, turn off the fan when the grain temperature at the top drops below 25°F.
- e) After December 15, shut off fan when the grain temperature at the top drops below 25°F regardless of moisture content.^{3/}

Spring Start-Up

- a) Start up and run continuously after March 15 if the grain remaining in the of the bin is greater than 19% w.b.
- b) Start up and run continuously after April 1 if the grain remaining at the top is between 17% and 19%.
- c) Start up and run continuously after April 15 if the grain remaining at the top is below 17% and you want to dry down to the 14% range for full summer storage. If you are going to market at 15½%, you may only want to run the fan periodically since the average bin moisture content will probably be at or below 15½% when the top reaches 17%.

^{1/} These are general guidelines for running the fan. Specific weather conditions may influence these dates. In general, keep the fan running as long as average temperatures are above 25°F. When temperatures drop below these levels for significant periods of time, the fan can be shut off before the dates mentioned above. Drying proceeds slowly below 25°F; and, more importantly, as long as the grain is below 25°F deterioration rates will be low, even at higher moisture contents.

^{2/} During the winter check the top of the bin periodically for moisture build-up (particularly near the center) or an increase in grain temperature. Run the fan for a total of 6 to 8 hours every several weeks if the ambient temperature is between 20-30°F. This is particularly important following an extended period below 0-10°F.

^{3/} If one of the filling schedules discussed earlier is followed, corn moisture contents at the top of the bin will normally be 21% or below and drying can normally be safely completed in the spring. In rare circumstances corn above 21% may remain in the bin after the December 15 shutoff. This wet corn can be held through the winter at temperatures below 25°F. However, the risk of spoilage during spring drying at the high moisture contents is greatly increased; therefore, this corn should be fed, sold or dried in some other manner before spring.

Downspout angles for this corn should be at least 45° to insure gravity flow.

Fine material and broken corn increase the resistance to airflow which reduces total airflow; therefore, performance is better with cleaner corn and screening is highly desirable for natural-air drying. If the corn is not screened, reduce the rate of filling to compensate for reduced airflows. Since the fines tend to accumulate in the center, unloading some corn from the center when the bin is full will be beneficial.

It is important to keep grain level to promote uniform airflow. Grain spreading devices can help to distribute the grain. In many cases, some additional hand leveling should be considered in all cases when filling of the bin is completed. In fact, because resistance to airflow is typically greater in the center of the bin than at the outer edges due to increased levels of fine material in the center, "dishing out" the center of the bin is usually beneficial. Where possible, drawing grain out of the center unloading hopper of the bin helps to reduce the amount of grain to be moved when leveling or "dishing out" the bin center. It also removes some of the fine material in the center of the bin.

Flexibility of a Drying Bin

In many cases it will not be feasible to equip all storage bins with drying floors and fans capable of delivering 1 to 1.25 cfm/bu. However, having one or two bins equipped for combination drying can provide additional operating flexibility. For example, a drying bin(s) can be used as a dryeration cooling bin(s) with transfer to conventional aerated storage. After all of the conventional storage has been filled, the drying bin(s) can be used for combination drying.

A drying bin can be used in conjunction with conventional aerated storage to help meet peak drying capacity needs (Figure 9). When harvest is proceeding rapidly with high moisture content corn, grain can be dried to 20 to 22 percent and discharged hot to the drying bin for natural-air drying. This provides the drying capacity to meet rapid harvest rates. When there is a lull in the harvest due to weather or other down time, 19 to 21 percent grain can be drawn off of the top of the bin and further dried to obtain the desired moisture content for conventional aerated storage. The grain can be cooled in the dryer before discharge to storage or discharged hot, cooled, then stored. This technique can provide storage of corn at safe intermediate moisture contents for "leveling" the dryer load. Also, grain quality may be improved by drying in two steps from harvest moisture contents to moisture contents safe for conventional storage.

A drying bin filled late in the season can be used to hold 18 to 20 percent corn through the winter. This works well for livestock operations where grain fed during the winter does not have to be dried. The remainder can be dried with natural air in the spring. In a cash grain operation, 18 to 20 percent corn can be used to blend with corn that has been overdried. Again, in the spring the remainder can be dried with natural air.

Use of a drying bin in these ways can provide additional flexibility for

Figure 9. Flexibility of a drying bin.

the drying system. To take advantage of this flexibility, the drying bin must be properly placed in a well designed grain handling system.

ECONOMIC CONSIDERATIONS

Economic comparison of combination drying to conventional drying is complex. Energy costs for drying are only part of the total cost for the drying and storage operation. Investment costs for equipment must be considered in any complete analysis. Since each situation is different, this is difficult to generalize.

Using the results of Table 4, energy costs for conventional and combination drying can be calculated at various fuel and electricity prices (Table 12). These results show that there is a saving in cost of energy to dry in most situations. These savings may or may not be enough to justify conversion to a combination drying and storage system.

The following are some other factors to consider, both costs and benefits. Potential additional costs:

1. Equipping storage bins with drying floors and drying fans.
2. Shallower bin depths (16 to 20 feet maximum drying depth desirable) to facilitate natural-air drying may lead to more expensive storage structures than deeper bins possible with conventional drying and storage.
3. Providing electrical service to meet increased demand for power.
4. Modifying materials handling capacities between the high-speed dryer and drying bins to accommodate handling hot, wet grain.
5. Reduced storage capacity in existing bins with combination drying due to a) space lost for drying floor and plenum, b) requirement of level filling for natural-air drying (not filling above the eaves), and c) lost space because fewer dry bushel equivalents of wet corn can be stored in the same volume compared to dry corn (a bin may hold 8 to 10 percent less dry bushels when filled with wet corn because of the extra moisture in the grain and test weight differences). Extra wall height (another ring) can be added at the time of construction for new bins at relatively low cost to minimize storage loss problems.
6. Costs incurred because it may be more difficult to reach the specific moisture content desired for marketing. The final moisture content with natural-air drying may be more variable than with conventional drying because of varying weather conditions. If, for example, grain were overdried

Table 12. Comparison of energy costs for conventional and combination drying in ¢/bu.^{1/}

Init. M.C., %w.b.	Elect., ¢/kWh	Propane, \$/gal (Natural gas, \$/mcf)									
		0.20 (2.18)		0.30 (3.28)		0.40 (4.37)		0.50 (5.46)		0.60 (6.55)	
		cv	cb	cv	cb	cv	cb	cv	cb	cv	cb
28.5	2	5.8	4.2	8.6	5.4	11.4	6.6	14.2	7.8	16.9	9.0
	3	6.0	5.0	8.7	6.2	11.5	7.5	14.3	8.7	17.1	9.9
	4	6.1	5.9	8.9	7.1	11.6	8.3	14.4	9.5	17.2	10.8
	5	6.2	6.7	9.0	8.0	11.8	9.2	14.6	10.4	17.3	11.6
	6	6.3	7.6	9.1	8.8	11.9	10.0	14.7	11.3	17.5	12.5
25.5	2	4.3	3.0	6.4	3.7	8.4	4.4	10.5	5.0	12.5	5.7
	3	4.4	3.9	6.5	4.5	8.5	5.2	10.6	5.9	12.6	6.5
	4	4.5	4.7	6.6	5.4	8.6	6.0	10.7	6.7	12.7	7.4
	5	4.6	5.5	6.7	6.2	8.7	6.9	10.8	7.6	12.8	8.2
	6	4.7	6.4	6.8	7.1	8.8	7.7	10.9	8.4	12.9	9.1

^{1/} Estimates based on energy use data from Table 4. Conventional drying to 15.5%; combination drying to 20.5% then completed with ambient air to 15.5%.

^{2/} cv - conventional drying; cb - combination drying.

to 13.5 percent due to natural-air drying when it was desired to market at 15.5 percent, the approximate 2.3 percent loss in weight represents a cost of 4.6¢/bu at \$2.00/bu corn and 6.9¢/bu at \$3.00/bu corn. Good management should help to avoid such overdrying in the natural air phase. This is not a problem with grain that is fed to livestock.

Potential additional economic benefits:

1. Increased drying capacity in the high-speed dryer may allow a smaller and less costly dryer or delay the need to expand high-speed capacity.
2. Improved grain quality may result in improved grade and, therefore, price for corn that is marketed.
3. Availability of an alternate form of energy (electricity) may extend the propane fuel in years of short supply and, therefore, allow more timely harvesting with reduced field losses.
4. Higher airflows used in natural-air drying provide improved ability to handle storage problems.

To provide an estimate of the economic return associated with investment in equipment for combination drying, a comparison was made based on conventional and combination systems set up to handle 40,000 bushels per year. There are many sizes and variations that could have been considered; however, it is felt that this is a realistic size system for utilization of combination drying.

New construction was considered in all cases. Two combination systems and one conventional system were specified as indicated in Figure 10. Two combination systems were studied to provide an indication of tradeoffs in bin diameter, grain depth and fan horsepower. One combination system consists of two 48-ft diameter bins with grain depths of approximately 16 ft and two 7½-hp fans on each bin. This leads to an estimated airflow of 1.25 cfm/bu when full. The other system uses two 42-ft diameter bins with grain depths of approximately 20 ft and two 10-hp fans on each bin. This results in an estimated airflow of 1.1 cfm/bu. These bin dimensions and fan sizes are based on selection of actual equipment from product literature. The dryer, cleaner, wet holding bin, augers and related equipment are sized the same for both combination systems with the exception of minor differences in auger lengths.

The bins for the conventional system are equipped for storage only and do not include full drying floors or drying fans. Aeration systems equipped to provide airflows of 0.1 cfm/bu are specified. Other equipment is essentially the same as for the combination systems with the exception that the dryer selected has a nominal capacity rating of 270 bu/hr drying from 25 to 15 percent with in-dryer cooling compared to a rating of 150 bu/hr under the same conditions for the dryer selected for the combination systems. Of course, the dryer in the combination system is required to remove less moisture than the dryer in the conventional system and cooling is done in the bin so that this smaller unit provides at least equivalent capacity to the larger unit when operated in the combination mode.

CONVENTIONAL SYSTEM
(40,000 BU)

COMBINATION SYSTEMS
(40,000 BU)

OR

Figure 10. Schematic diagrams of systems used in economic analysis.

First costs for the systems as specified were developed by a local dealer based on summer 1980 prices. Total system costs including concrete work, labor for construction and freight as well as equipment were estimated. The only factor not included is the cost of electrical connection since the equipment dealer who provided the estimate normally does not perform that work as part of his installation package. There should not be a major cost differential between the conventional and combination systems for electrical connections as long as the required electrical service is available at the farm. The connected horsepower required for the dryer and aeration fans in the conventional system is approximately 25 hp compared to a requirement of approximately 40 or 50 hp for the fans on the dryer and drying bins in the combination systems. These are in addition to the motors on the augers which are the same in both systems. If adequate power is not available at the farm for the additional electrical load required for combination drying, significant additional expense could be incurred to provide the service, depending on the situation. In these comparisons it is assumed that adequate electrical service is available at the farm.

Alternatives are compared based on after-tax rate of return corrected for inflation. The calculation of rate of return is based on a net present value analysis. Some of the major assumptions and factors included in the analysis are indicated below:

1. Twenty-year planning period.
2. Ten-year life for equipment involving motors or moving parts such as augers, fans, dryers. Twenty-year life for structures such as bins, concrete, etc.
3. Seven-year depreciation schedule for equipment. Fifteen-year depreciation schedule for structures. Declining balance (150% factor) depreciation schedule.
4. A seven-year loan for eighty percent of the first cost assumed for all investments.
5. Ten percent investment credit assumed on all investments.
6. Thirty-five percent marginal tax rate assumed.

Investment costs for the three systems are presented in Table 13. Costs in the equipment category are less for the combination systems because a smaller dryer is required than for conventional drying. Costs are higher in the bin and structure category for combination drying because of the larger bin floor area and full drying floors.

Energy requirements used in the analysis are shown in Table 14. The values for conventional drying and combination drying with 48-ft diameter bins are based on results from Table 4. Energy requirements for the ambient air phase of drying in the 42-ft diameter bins are higher than in the 48-ft diameter bins because of the greater grain depths in the 42-ft diameter bins. The nominal power input to each 42-ft diameter bin is 20-hp compared to 15-hp to each 48-ft diameter bin. Airflows are 1.1 cfm/bu for each 42-ft diameter

Table 13. Investment costs for three 40,000 bushel drying-storage systems.

	Conventional	Combination	
		42' dia. bin	48' dia. bin
Equipment ^{1/} (Fans, motors, augers, etc.)	\$30,147	\$25,239	\$25,325
Bins and ^{2/} Structures	34,387	49,150	56,257
Total	\$64,534	\$74,389	\$81,582

^{1/} Ten-year life assumed.

^{2/} Twenty-year life assumed.

Table 14. Energy requirements for three systems.

Drying System	Initial Moisture Content, % w.b.			
	25.5		28.5	
	Propane, gal	Electric, kWh	Propane, gal	Electric, kWh
Conventional ^{1/} High-temp. to 15.5% in-dryer cooling. (36' diameter bins)	0.205	0.10	0.270	0.13
Combination ^{1/} Discharge hot, 21.5% in storage after cool- ing, dry to 15.5% with ambient air. (48' diameter bins)	0.067	0.84	0.122	0.86
Combination ^{2/} Discharge hot, 21.5% in storage after cooling, dry to 15.5% with ambient air. (42' diameter bins)	0.067	1.11	0.122	1.13

^{1/} Based on data from Table 4.

^{2/} Electrical energy for ambient air drying increased by 33 percent compared to 48-ft diameter bin due to greater grain depths and higher fan power requirements.

bin and 1.25 cfm/bu for each 48-ft bin; however, the higher power input coupled with a lower airflow to the 42-ft diameter bins leads to a higher temperature rise for drying air than for the 48-ft diameter bins. Therefore, it is assumed that the drying times for the ambient air phase are equivalent for the two combination systems, the greater temperature rise in the air for the 42-ft diameter bin compensating for the lower airflow. Since the power input is 33 percent greater for the 42-ft diameter bins than for the 48-ft diameter bins, the electrical energy input for the ambient air phase is also 33 percent larger.

Rate of return (after taxes and corrected for inflation) is presented in Figure 11 as a function of propane and electricity fuel inflation rates which are assumed to be equal for this particular comparison. Other key parameters are: general inflation rate = 8 percent; interest rate = 12 percent, marginal tax rate = 35 percent; drying from 25.5 to 15.5 percent. Results are presented for several combinations of initial (1980) propane and electricity prices. Rate of return increases as energy (propane and electric) inflation increases. Rates of return are higher in all cases for the combination system with 42-ft diameter bins than for the system with 48-ft diameter bins. At an energy inflation rate of 8 percent which is equal to the general inflation rate, the rates of return range from approximately 5 to 24 percent depending on bin diameter and initial energy prices. It should be remembered that these rates of return are corrected for inflation (i.e., in terms of constant 1980 dollars). Often rate of return comparisons are presented in terms of the discount rate or rate of return not corrected for general inflation. The results of Figure 11 can be approximately compared on this basis by adding the general inflation rate to the rate of return obtained from the graph. Therefore, at an energy price inflation rate of 8 percent (equal to general inflation rate) the rates of return not corrected for inflation (i.e., discount rates) range from approximately 13 to 32 percent.

Similar results are presented in Figure 12 for drying from 28.5 to 15.5 percent. Compared to Figure 11 the rates of return are higher due to increased propane savings that result because drying starts at a higher moisture content.

Results in Figure 13 indicate sensitivity of rate of return to changes in general inflation rate, interest rate and marginal tax rate. Rates of return decrease as marginal tax rate increases from 35 to 45 percent (comparing curves A vs. B and curves F vs. G). Rates of return also decrease as the general inflation rate increases from 8 to 10 percent (comparing curves A vs. C and curves F vs. H). Rates of return decrease as the interest rate increases from 12 to 14 or 20 percent (comparing curves C vs. D vs. E and curves H vs. I vs. J). In general, it appears that rate of return is much less sensitive to changes in these factors than to changes in initial propane and electricity prices as shown in Figures 11 and 12.

Comparisons in Figures 14 and 15 involve differential changes in propane and electricity inflation rates. In Figure 14 propane inflation rate is assumed to vary while electrical energy inflation rate is held constant at the general inflation rate of 8 percent. These results show that at low propane inflation rates under certain energy price conditions the rate of return for the system with 48-ft diameter bins may exceed the rate of return for the system with 42-ft diameter bins (e.g., curves C vs. D below 4.4 percent inflation rate and curves E vs. F below 7.4 percent inflation rate).

CURVE	BIN DIA., FT.	PROP. PRICE, ¢/GAL.	ELECT. PRICE, ¢/KWH
A	42	60	4
B	48	60	4
C	42	60	5
D	48	60	5
E	42	50	5
F	48	50	5

GENERAL INFLATION RATE = 8 PERCENT

INTEREST RATE = 12 PERCENT

MARGINAL TAX RATE = 35 PERCENT

Figure 11. Rate of return (corrected for inflation) versus energy inflation rate.

CURVE	BIN DIA., FT.	PROP. PRICE, ¢/GAL.	ELECT. PRICE, ¢/KWH
A	42	60	4
B	48	60	4
C	42	60	5
D	48	60	5
E	42	50	5
F	48	50	5

GENERAL INFLATION RATE = 8 PERCENT

INTEREST RATE = 12 PERCENT

MARGINAL TAX RATE = 35 PERCENT

Figure 12. Rate of return (corrected for inflation) versus energy inflation rate.

Figure 13. Rate of return (corrected for inflation) versus energy inflation rate.

CURVE	BIN DIA., FT.	PROP. PRICE, ¢/GAL	ELECT. PRICE, ¢/KWH
A	42	60	4
B	48	60	4
C	42	60	5
D	48	60	5
E	42	50	5
F	48	50	5

GENERAL INFLATION RATE = 8 PERCENT

INTEREST RATE = 12 PERCENT

ELECTRICITY INFLATION RATE = 8 PERCENT

MARGINAL TAX RATE = 35 PERCENT

MOISTURE REMOVED
25.5 % - 15.5 %

Figure 14. Rate of return (corrected for inflation) versus propane inflation rate.

In Figure 15 electricity inflation rate is assumed to vary while propane inflation rate is held constant at the general inflation rate of 8 percent. At high (above 8 percent) electricity inflation rates, the rate of return for the system with 48-ft diameter bins exceeds the rate of return for the system with 42-ft diameter bins (e.g., curves A vs. B above approximately 14.5 percent inflation rate, curves C vs. D above approximately 11.1 percent inflation rate, and curves E vs. F above approximately 8.9 percent inflation rate).

The preceding results have indicated that the bin diameter and, therefore, depth for the ambient air phase of combination drying that yields the greater rate of return is particularly sensitive to electrical energy prices and inflation rates. Results in Figure 16 are rates of return plotted as a function of energy price inflation rates (propane and electricity assumed equal) for a range of initial (1980) electricity prices. The initial propane price is 60¢/gallon. These results indicate that rates of return for the two combination systems are approximately equal at initial electricity prices of 6¢/kWh over the range of energy price inflation rates. Below 6¢/kWh the system with 42-ft diameter--18-ft deep bins provides a higher rate of return. Above 6¢/kWh the 48-ft diameter--16-ft deep bins provide a higher rate of return. These results should be transferable to bins of similar depths and airflow rates (cfm/bu).

These results generally indicate positive rates of return (corrected for inflation) over a wide range of energy prices and inflation rates for investments in combination drying systems. They should be applicable to new construction of systems in the size range most readily adaptable to combination drying. The results also provide indication of potential positive rate of return for modification of existing systems for combination drying. In many instances farmers need to increase drying capacity as a result of increased production. Since the combination approach usually results in at least a doubling of high-speed dryer capacity, selection of this option can make it possible for the farmer to forego costly modifications in the high-speed drying system with a potentially modest investment in equipment.

NATION WIDE ENERGY IMPACT

Shifts to combination drying from conventional drying will involve individual decisions by thousands of farmers. In addition, each farmer has the option of using the technology on only part of his production. Therefore, the analysis will be based on total U.S. corn production.

The 1978 U.S. corn for grain production estimate is 7.1 billion bushels. Assuming that 70 percent is dried artificially, the total is 5 billion bushels (7.1×0.7). Of the corn that is dried artificially, it is estimated that approximately 60 percent is dried on-farm. The other 40% is dried commercially. The installations that have potential for shifting to combination drying are primarily located on-farm. Therefore, the estimated 3 billion bushels dried on-farm (5×0.6) will be used in the analysis. Propane is the fuel that is used in virtually all on-farm drying installations. Based on USDA data (Torgerson and Cooper, 1980), 1978 on-farm propane use for corn drying is estimated to be approximately 435 million gallons. This amounts to 0.145 gallons per bushel dried. No data are available on the average amount of moisture removed on a nation-wide basis. However, if it is assumed that

CURVE	BIN DIA., FT.	PROP. PRICE , ¢/GAL.	ELECT. PRICE , ¢/KWH
A	42	60	4
B	48	60	4
C	42	60	5
D	48	60	5
E	42	50	5
F	48	50	5

GENERAL INFLATION RATE = 8 PERCENT

INTEREST RATE = 12 PERCENT

PROPANE INFLATION RATE = 8 PERCENT

MARGINAL TAX RATE = 35 PERCENT

MOISTURE REMOVED

25.5 % - 15.5 %

Figure 15. Rate of return (corrected for inflation) versus electricity inflation rate.

CURVE	BIN DIA., FT.	ELECT. PRICE, ¢/kWH
A	42	4
B	48	4
C	42	5
D	48	5
E	42	6
F	48	6
G	42	7
H	48	7
I	42	8
J	48	8

RATE OF RETURN
 NEGATIVE FOR ALL
 INFLATION RATES

GENERAL INFLATION RATE = 8 PERCENT

INTEREST RATE = 12 PERCENT

MARGINAL TAX RATE = 35 PERCENT

PROPANE PRICE = 60 ¢/GAL

MOISTURE REMOVED

25.5 % - 15.5 %

Figure 16. Rate of return (corrected for inflation) versus energy inflation rate.

existing drying is done with conventional systems requiring an average of 2450 Btu/lb water removed, the average moisture removal is estimated to be 23 percent to 15.5 percent. At this level of moisture removal the estimates are made for energy use and cost per bushel for conventional and combination drying in Table 15.

Table 15. Estimated energy use and cost per bushel for conventional and combination drying.

	Drying Method	
	Conventional	Combination
Propane, gal/bu	0.145	0.036
Electric, kWh/bu	0.07	0.73
Propane, Btu/bu (@ 92,000 Btu/bu)	13,340	3,312
Electricity, Btu/bu (@ 10,500 Btu/bu)	735	7,665
Total, Btu/bu	14,075	10,977
Propane, \$/bu (@ \$0.60/gal or \$6.52/million Btu)	0.087	0.022
Electricity, \$/bu (@ \$0.05/kWh or \$4.76/million Btu)	0.004	0.037
Total, \$/bu	0.091	0.059

The percentage of total production that will convert to the new technology is difficult to estimate. Farmers are making decisions to shift part or all of their drying to this system as needs for expansion as well as new construction occur. Since the technology has advantages of increased drying capacity and improved grain quality in addition to energy savings, farmers will consider these factors in their decisions.

Table 16 provides comparisons of U.S. energy use for drying corn for a range of from 100 percent conventional-0 percent combination to 50 percent conventional-50 percent combination.

Table 16. Estimated U.S. energy use at various levels of conventional versus combination drying.

	Percent Conventional-Combination					
	100-0%	90-10%	80-20%	70-30%	60-40%	50-50%
Energy Use/Year						
Propane, million gal	435	402	370	337	304	272
Electric, million kWh	210	408	606	804	1002	1200
Propane, trillion Btu	40.0	37.0	34.0	31.0	28.0	25.0
Electric, trillion Btu	2.2	4.3	6.4	8.4	10.5	12.6
Total, trillion Btu	42.2	41.3	40.4	39.4	38.5	37.6
Energy Saving/Year						
Propane, million gal	---	33	65	98	131	163
Electric, million kWh	---	-198	-396	-594	-792	-990
Total, trillion Btu	---	0.9	1.8	2.8	3.7	4.6
Dollar Savings/Year						
Propane, million \$	---	19.8	39.0	58.8	78.6	97.8
Electric, million \$	---	- 9.9	- 19.8	- 29.7	- 39.6	- 49.5
Total, million \$	---	9.9	20.2	29.1	39.0	48.3

The rate of adoption of combination drying is hard to estimate. Some operations are not readily adaptable to combination drying and producers will not choose that route. However, many operations will use combination drying for part of their production. A practical estimate might be for a shift of up to 30 percent of the drying from conventional to combination drying spread over the next 10 years. As a result the estimated annual savings in propane or propane equivalent would be 9 trillion Btu's/year with an increase in electrical energy use of 6.2 trillion Btu's/year after 10 years.

- A final point to be made is that the increased electrical energy use occurs primarily in the months of October and November in the fall and possibly again in the spring in April and early May which are between the heating and air-conditioning peaks for the electrical generating system. Therefore, the increased electrical load should not lead to need for new generating capacity, and in fact may help to fill current slack periods as far as electrical demand is concerned.

CONCLUSIONS

1. Combination drying significantly reduces propane or natural gas fuel requirements with an increase in electrical energy for drying.
2. Total energy equivalent of propane or natural gas, and electricity as metered on the farm is reduced with combination drying.
3. High-speed dryer capacity is significantly increased with combination drying. Grain quality also is improved.
4. Addition of supplemental heat to the in-storage phase of drying provides a modest increase in drying reliability and some reduction in fan energy requirements.
5. Supplemental heat for in-storage drying from a fossil-fuel-derived source increases the total energy input for drying as compared to ambient-air drying.
6. Energy cost savings exist for combination drying at most levels of fuel cost. Investment costs for equipment modifications, which vary significantly from situation to situation, will determine whether it is feasible to adopt combination drying. An example economic analysis for a 40,000 bushel-per-year system showed favorable rates of return for combination drying over a wide range of conditions.
7. Currently, the factors that may provide the greatest incentives to shift to combination drying include: 1) increased drying capacity, and 2) increased flexibility of energy source (propane or electric).

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