5-2000

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Repository Citation

Montross, Michael D. and Maier, Dirk E., "Simulated Performance of Conventional High-Temperature Drying, Dryeration, and Combination Drying of Shelled Corn with Automatic Conditioning" (2000). *Biosystems and Agricultural Engineering Faculty Publications*. 101.
https://uknowledge.uky.edu/bae_facpub/101

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Notes/Citation Information
Published in *Transactions of the ASAE*, v. 43, issue 3, p. 691-699.

Digital Object Identifier (DOI)
https://doi.org/10.13031/2013.2751

SIMULATED PERFORMANCE OF CONVENTIONAL HIGH-TEMPERATURE DRYING, DRYERATION, AND COMBINATION DRYING OF SHELLED CORN WITH AUTOMATIC CONDITIONING

M. D. Montross, D. E. Maier

ABSTRACT. *Combination drying, based on computer simulation, was evaluated as an alternative drying technique to traditional high-temperature drying and dryeration. Simulation models of high-temperature crossflow drying and in-bin drying and conditioning were used to evaluate the performance of conventional crossflow drying and full-heat crossflow drying followed by dryeration or natural-air drying for Indianapolis, Indiana, and Des Moines, Iowa. Energy costs from propane, electricity, moisture shrink below the market moisture content, and dry matter loss were estimated to find the total average drying cost over 29 years. Dryeration and combination drying reduced the total drying cost by approximately 10% compared to conventional drying and cooling within the dryer at current economic conditions. The greatest benefit was an increase of 72 and 159% in drying capacity when dryeration and combination drying were used instead of conventional drying and cooling within the dryer, respectively. However, the economic return of combination drying could be improved by the development of natural-air drying techniques or controllers that would limit the predicted moisture shrink loss.*

Keywords. *Two-stage drying, Dryeration, Natural-air drying, Aeration controllers.*

Frequently the capacity of a drying system and the quality characteristics of the dried product need to be improved. High-temperature grain drying involves the use of air heated with propane or natural gas to a temperature of 50 to 300°C depending on the dryer type, the crop to be dried, and the desired grain quality characteristics (Brooker et al., 1992). Crossflow dryers are commonly found as part of an on-farm high-temperature drying system. Crossflow dryers with a drying and cooling section generally produce grain of lower quality compared to other drying techniques, and are one of the least efficient in terms of energy consumption.

Energy efficiency and capacity increase as the drying-air temperature increases. However, increasing the drying-air temperature leads to a decrease in grain quality. Stress-cracking in corn is a quality indicator frequently used by engineers and millers to determine the severity of damage done during drying. The percentage of stress-cracked kernels is correlated with the breakage susceptibility in corn (Thompson and Foster, 1963), and with a decrease in corn dry milling performance (Paulsen and Hill, 1985). The grain kernel temperature (Watkins and Maier, 1997, 1998) and the final moisture content after drying (Thompson and Foster, 1963) also have a significant effect on the breakage susceptibility and percentage of stress cracked kernels. If corn is dried to lower moisture contents using high temperatures, more stress cracks will develop. Gustafson and Morey (1979) analyzed the variables during drying that contribute to changes in grain quality. They determined that delayed cooling effectively reduces possible breakage susceptibility and results in improved test weights over conventional drying and cooling within the dryer.

Dryer capacity and grain quality can be increased if corn is discharged from the dryer at a higher moisture content before it is cooled. Transferring hot, partially dried corn converts a drying system that generally exceeds maximum allowable kernel temperatures into one with lower kernel temperatures. Kernel temperatures should be kept below 60°C when drying high quality U.S. No. 2 yellow corn, waxy, high amylose, and high oil corn, and below 43°C when drying white and yellow food grade corn to limit stress-cracking and breakage susceptibility. High-speed cooling within the dryer results in a significant increase in stress cracks and breakage susceptibility (Thompson and Foster, 1963). Discharging hot, partially dried corn into a bin and delaying cooling allows for one of two processes, dryeration or combination drying, to be used. Both processes will reduce the number of stress-cracked kernels that develop compared to conventional high-temperature crossflow drying.

Dryeration was introduced as a method to increase dryer capacity, improve energy efficiency, and increase grain quality (Foster, 1964; McKenzie et al., 1967). Dryeration involves drying with a high capacity dryer, tempering in a bin, followed by cooling in the same bin before transfer to final storage. When using a multi-stage high capacity dryer all stages are operated with full heat. This increases the drying capacity by 50 to 75% due to a number of factors:

Article was submitted for publication in June 1999; reviewed and approved for publication by the Food & Process Engineering Institute of ASAE in March 2000. Presented as ASAE Paper No. 94-6042.

Purdue University Agricultural Research Programs, Manuscript No. 16017. Trade names are used in this study solely to provide specific information. Mention of a trade name does not constitute a warranty of the product to the exclusion of other products not mentioned.

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All moisture contents are in percent wet basis (w.b.), unless otherwise noted.

eliminating cooling within the dryer, removal of less moisture, and an increase in the amount of heated air used. The corn is discharged hot between 43 and 54°C from the dryer into a separate bin without cooling and at a moisture content two or three percentage points higher than desired. After tempering for 8 to 12 h, the grain is cooled with ambient air at an airflow rate of 0.6 to 0.8 m^3 min^{-1} t^{-1}. Delayed cooling allows a large percentage of the sensible heat in the corn to be used for evaporating the remaining moisture. Multiple (checked) stress cracks typically are reduced from over 40% to less than 10% when dryeration is used over conventional high-temperature drying (Foster, 1973). The disadvantages of dryeration are the increased grain handling and the additional equipment needed for tempering. Bins need to be equipped with larger fans to deliver airflows of at least 0.6 m^3 min^{-1} t^{-1}.

A modification of the dryeration process is in-bin cooling, which combines tempering and cooling within the same bin. It is generally recommended to avoid removal of more than two percentage points of moisture if the cooled corn is left in the same bin for storage. Condensation can be a significant problem when using dryeration or in-bin cooling and needs to be carefully managed using roof vents, open eave bins, roof exhausters, and possibly perforated air tubes along the sidewalls.

In combination drying, a high-capacity dryer is used to lower the corn moisture to 20 to 22% wet basis (Driscoll and Srzednicki, 1996). With a multi-staged high capacity dryer, all stages are operated in full heat mode. Partially dried corn is discharged from the dryer and transferred into a natural-air (NA) in-bin drying system. After a tempering period, the corn is cooled and dried using natural-air or low-temperature air. Combination drying has three advantages over conventional high-temperature drying—reduced energy consumption, increased drying capacity, and increased grain quality (Morey, 1977). A major disadvantage of combination drying is the extra equipment and management required, including larger fans to produce a higher airflow rate than used in a conventional storage bin. With conventional high-temperature drying systems the storage bins are equipped with relatively small aeration fans that usually deliver 0.1 m^3 min^{-1} t^{-1}. Natural-air drying requires fully perforated drying floors and larger fans to dry the grain with an airflow of at least 1.1 m^3 min^{-1} t^{-1}. Also, NA drying generally incurs a larger variability in final moisture content, moisture uniformity, dry matter loss (DML), and total drying costs.

Morey et al. (1981) performed a number of field trials and computer simulations to demonstrate the feasibility of using combination drying compared to conventional high-temperature drying. Their results indicated that combination drying significantly reduced the propane or natural gas consumption with an increase in electric requirements for drying.

Although the benefits of combination drying appear obvious, the potential long-term economic gain for the Midwestern Corn Belt need to be further quantified. Thus, this simulation study was initiated to estimate the increase in drying capacity and changes in operating costs by utilizing dryeration or combination drying compared to conventional drying and cooling within a high-temperature crossflow dryer.

OBJECTIVES

1. Evaluate the feasibility of dryeration and combination drying of corn in the eastern (Indianapolis, Indiana) and western (Des Moines, Iowa) Corn Belt using computer simulation.
2. Estimate the relative performance and costs of conventional high-temperature drying, dryeration, and combination drying based on computer simulation.

SIMULATED CROSSFLOW DRYING

CROSSFLOW DRYING PROCEDURES

A Farm Fans C2125A crossflow dryer (FFI Corporation, Indianapolis, Indiana) was used as the standard high-temperature dryer for the simulation analysis. According to the manufacturer's specifications, the dryer has a column width of 0.36 m. The height of the drying column is 2.5 m and the height of the cooling column is 1.25 m. The overall length of the dryer is 4.9 m. Airflow rates are 91 m^3 min^{-1} t^{-1} in the drying section and 119 m^3 min^{-1} t^{-1} in the cooling section. The model from Liu and Bakker-Arkema (1997) was used to simulate crossflow drying.

Three drying strategies, full heat crossflow drying followed by NA drying, full heat crossflow drying followed by dryeration, and conventional drying and cooling (DC) within the dryer, were investigated. To determine average ambient conditions for dryer operations, long-term average wet-bulb temperatures and wet-bulb depressions were determined from maps (ASAE, 1988). For any harvest date, an average ambient temperature of 13.3°C and a relative humidity of 66% were used for both Des Moines, Iowa, and Indianapolis, Indiana. Based on the maps of the wet-bulb temperature and wet-bulb depression, it was assumed that there was no significant difference in the ambient conditions between Des Moines and Indianapolis when simulating the performance of the high-temperature dryer for any harvest date.

Two sets of drying-air temperatures were used in the simulation study. The high temperatures were the maximum recommended by the dryer manufacturer and a lower set of temperatures was investigated to minimize the maximum kernel temperature during drying. Three initial moisture contents (22, 25, and 28%) that are typically encountered during harvest were used to demonstrate the feasibility of combination drying. Energy use by the crossflow dryer was calculated by summing the LP gas and electric consumption during drying and dividing by the mass of water removed. Overall energy use of the drying and storage strategies was determined by summing the energy consumed by the crossflow dryer and the electricity required for in-bin cooling and NA drying.

DRYING AND COOLING WITHIN THE DRYER (DC)

It was assumed that during DC, the moisture content out of the dryer was 15.5%, and that after in-bin aeration the corn would reach the desired moisture content of 14.5%, which is the recommended long-term safe storage moisture content (MWPS, 1988). Drying-air temperatures of 99 and 82°C were investigated. Table 1 summarizes the performance of the crossflow dryer if drying and cooling occurred in the dryer.

Table 1. Simulated results for conventional crossflow drying and cooling (DC), full heat crossflow drying followed by dryeration (Dryeration), and full heat crossflow drying followed by natural-air in-bin drying (Combination)

Drying Method	Top Stage Temp (°C)	Bottom Stage Temp (°C)	MCin (% w.b.)	MCout (% w.b.)	Outlet Corn Temp (°C)	Capacity (m³/h)	Energy Use by Crossflow Dryer* (kJ/kg water)
DC	99	13	22.0	15.5	18	14.1	5475
DC	99	13	25.0	15.5	15	10.7	5090
DC	99	13	28.0	15.5	14	8.9	4800
DC	82	13	22.0	15.5	15	10.5	5945
DC	82	13	25.0	15.5	13	7.9	5565
DC	82	13	28.0	15.5	13	6.4	5235
Dryeration	110	77	22.0	17.0	57	25.8	6030
Dryeration	110	77	25.0	17.0	58	18.5	5440
Dryeration	110	77	28.0	17.0	58	14.8	5075
Dryeration	99	71	22.0	17.0	55	22.2	6255
Dryeration	99	71	25.0	17.0	56	15.9	5655
Dryeration	99	71	28.0	17.0	56	12.8	5255
Combination	110	77	22.0	20.0	49	49.3	7595
Combination	110	77	25.0	20.0	54	27.7	5580
Combination	110	77	28.0	20.0	55	19.9	5000
Combination	99	71	22.0	20.0	47	46.9	7140
Combination	99	71	25.0	20.0	52	24.5	5650
Combination	99	71	28.0	20.0	53	17.3	5450

* kJ/kg water = LP gas and electrical energy used by the crossflow dryer divided by water removed while corn was in the dryer.

By decreasing the drying-air temperature, drying capacity decreased and energy use increased. For corn dried at 99 versus 82°C, the capacity of the dryer decreased by approximately 26% and the energy use increased by 9% for all moisture contents. The energy use of the high-temperature dryer could be reduced if the exhaust air was recirculated, however this was not considered.

The average corn temperature out of the dryer for all drying-air temperatures and initial moisture contents ranged between 13 and 18°C. The predicted maximum kernel temperature was approximately 79°C when the high drying-air temperature was used, and 70°C when the low drying-air temperature was used. Both drying-air temperatures led to kernel temperatures that were too high if stress cracks are to be avoided. Additionally, the maximum kernel temperature was not significantly influenced by the initial moisture content (less than 1°C).

FULL HEAT DRYING AND DRYERATION

During full heat drying followed by dryeration, the desired outlet moisture content from the crossflow dryer was 17.0%. The top stage burner was set to deliver a drying-air temperature of 110°C and the bottom stage was set at 77°C. Drying-air temperatures of 99°C in the top stage and 71°C in the bottom stage were also investigated. Table 1 summarizes the performance of the crossflow dryer during full heat drying followed by dryeration. By employing full heat drying, the capacity of the dryer increased by 83, 73, and 66% when comparing the maximum drying-air temperatures for dry and cool (DC) versus full heat drying of corn initially at 22, 25, and 28%, respectively. The increase in capacity was even greater when the lower drying-air temperatures were compared; capacity increases were 111, 101, and 99% for 22, 25, and 28% initial moisture content, respectively.

Although capacity increased dramatically, energy use by the crossflow dryer per unit of water removed in the dryer increased by 10, 7, and 6% for the high drying-air temperatures, and by 5, 2, and 0% for the lower drying-air temperatures for 22, 25, and 28% moisture contents, respectively. The increase in energy use was due to the corn being discharged from the dryer at an elevated temperature and moisture content with dryeration compared to DC. The energy in the hot corn was utilized during the in-bin cooling process to remove additional moisture, which improves the overall drying efficiency. If electricity use during dryeration was included in the energy use calculations, the numbers dropped to 4250, 4170, and 4015 kJ/kg water removed for the high drying-air temperatures for initial moisture contents of 22, 25, and 28%, respectively. Maximum kernel temperatures within the dryer were 80°C if the high drying-air temperatures were used, and a maximum kernel temperature of 75°C occurred with the lower drying-air temperatures. There was a small difference (less than 1°C) in the predicted maximum kernel temperature for the three harvest moisture contents investigated. Both drying-air temperatures exceeded the maximum kernel temperatures desired for drying high quality corn, although they occurred at higher moisture contents, which results in a lower potential for stress-crack formation (Foster, 1973).

FULL HEAT DRYING AND NA IN-BIN DRYING

During full heat drying followed by NA in-bin drying (combination drying) the desired outlet moisture content from the crossflow dryer was 20%. Table 1 summarizes the performance of the crossflow dryer. Dryer capacity increased by 250, 159, and 123% over DC, and by 91, 50, and 35% over full heat drying followed by dryeration at the higher drying-air temperatures for initial moisture contents of 22, 25, and 28%, respectively. Energy use for the dryer increased by 39, 10, and 4% over DC and by 26, 3, and –1% over full heat drying followed by dryeration at the higher drying-air temperatures for initial moisture contents of 22, 25, and 28%, respectively. Combination drying significantly increased the drying capacity compared to dryeration and DC. Average outlet corn temperatures ranged from 47 to 55°C. Maximum kernel temperatures of 77°C occurred when the high drying-air temperatures were used and 72°C when the low drying-air temperatures were used. For all high-temperature drying strategies investigated, the maximum allowable kernel temperatures required for food corn (43°C) or for waxy corn (60°C) were exceeded. However, with combination drying and dryeration, the maximum kernel temperatures occurred at higher moisture contents compared to DC. The initial moisture content had a minor influence on the predicted maximum kernel temperature (less than 3°C).

CROSSFLOW DRYING COST COMPARISONS

Table 2 summarizes the simulated energy costs required to operate the crossflow dryer. The total cost to operate the crossflow dryer was calculated by summing the cost of LP

Table 2. High-temperature drying costs* ($/t)†

Drying Strategy	High Temperatures Initial MC 22%	High Temperatures Initial MC 25%	High Temperatures Initial MC 28%	Low Temperatures Initial MC 22%	Low Temperatures Initial MC 25%	Low Temperatures Initial MC 28%
DC	3.81	5.39	6.96	4.17	5.93	7.64
Dryeration	3.29	4.94	6.61	3.43	5.16	6.87
Combination	1.72	3.29	4.91	1.63	3.34	5.08

* Assuming an LP gas cost of 0.185 $/L and an electrical cost of 0.07 $/kWh.

† Based on 14.5% moisture content corn.

gas and electricity. It was assumed that the LP burner was 90% efficient and the electric motors were 80% efficient. The price of LP gas was assumed to be 0.185 $/L and the price of electricity 0.07 $/kWh. At the higher drying-air temperatures, the dryer was more energy efficient and therefore cost less to operate compared to the lower drying-air temperatures. As the initial moisture content increased, the drying time and the total drying cost increased. When drying was stopped at 17% moisture (dryeration) compared to drying to 15.5% moisture (DC), the high-temperature drying cost decreased by 14, 8, and 5% for initial moisture contents of 22, 25, and 28%, respectively, when the high drying-air temperatures were used. When drying was stopped at 20% moisture (combination drying) compared to drying to 15.5% moisture (DC), the high temperature drying costs decreased by 55, 39, and 29% for initial moisture contents of 22, 25, and 28%, respectively, when the high drying-air temperatures were used.

SIMULATED IN-BIN CONDITIONING

IN-BIN CONDITIONING PROCEDURES

After crossflow drying, the corn was assumed to be discharged into average sized farm bins with a diameter of 11 m, and a depth of 5.5 m, holding 392.4 t level filled. The desired moisture content during storage was assumed to be 14.5%. Table 3 summarizes the airflows, static pressures, and fan sizes used during storage and NA drying. During in-bin cooling, it was assumed that the fans would be throttled to limit the airflow to 0.6 m^3 min^{-1} t^{-1} until the corn temperature was below 20°C. Lower airflow rates allow for maximum moisture removal during cooling (Foster, 1973). The FANS program (University of Minnesota, 1997) was used to select and determine the airflow rates used during storage based on fan curve data from Farm Fans (FFI Corporation, Indianapolis, Indiana). Two airflow rates during full heat drying followed by dryeration, and full heat drying followed by NA drying were investigated. An existing finite difference model of NA drying and storage was used (Maier, 1992; Zink, 1998).

The airflow rates simulated for dryeration and NA drying are slightly greater than traditionally recommended. However, higher airflow rates allow for more flexible NA drying strategies and reduce the risk and variability when drying higher valued specialty crops. For DC it was assumed that the bin was filled with corn at a uniform temperature of 15°C and a uniform moisture content of 15.5%. When dryeration was used, the bin was filled with corn at a temperature of 57°C and a moisture content of 17%. When combination drying was used, corn at a temperature of 52°C and a moisture content of 20% was placed into the NA drying bin. It was assumed that the corn entering the bin for storage, dryeration, or NA drying was at the same moisture content and temperature regardless of initial moisture content, drying-air temperature, and harvest date used in the high-temperature drying step.

Table 3. Fan specifications used for the in-bin storage, dryeration, and NA drying simulations

Strategy	Fan Size (kW)	Airflow (m^3 min^{-1} t^{-1})	Static Pressure (Pa)
Dry/cool in dryer	3.7	0.6	350
Dryeration	3.7 or 7.5	0.6 or 1.0	350 or 705
Combination	22.4 or 37.3	1.7 or 2.2	1430 or 2100

All cost estimates presented are based on corn dried from an initial harvest moisture content of 25% and at the high drying-air temperatures. Twenty-nine years of hourly weather data from the National Climatic Data Center (1993) were used to evaluate maintenance aeration and natural-air drying strategies for two locations (Indianapolis, Indiana, and Des Moines, Iowa).

Average drying and conditioning costs were calculated by averaging the simulation results for NA drying and aeration using a commercial fan controller over 29 years. A major factor in utilizing any drying and storage strategy is the total cost per mass of grain handled. Ideally, the drying and storage strategies investigated would have 392.4 tons of corn at a moisture content of 14.5% in the bin after the storage period. Corn that has a moisture content less than 14.5% has less mass, and, therefore, a lower market value. The price of corn was assumed to be 93.75 $/t. A shrink cost was calculated based on the mass of water lost due to overdrying multiplied by the price of corn. If the corn was too wet due to underdrying, the mass of water that should have been removed during drying and conditioning was multiplied by the price of corn to apply a discount. The cost due to DML was defined as the percentage of dry matter that respired during storage multiplied by the price of corn as a continuous function of dry matter loss. Electrical costs were estimated by calculating the number of hours the fans operated multiplied by the fan power and the cost of electricity. A similar procedure to estimate the drying cost was used by Pierce and Thompson (1979).

After in-bin cooling was completed, the fan was operated at one of two airflow rates (1.7 or 2.2 m^3 min^{-1} t^{-1}). Continuous natural-air drying was simulated until the corn had an average moisture content of 15.5% or less and until the maximum moisture within the bin was less than the allowable limits (17 or 18%). After drying was completed, maintenance aeration was performed automatically by using a modified fan control mode of a commercial fan controller (SentryPAC by Sentry Technologies, Chico, California). No attempts were made to optimize NA drying or the maintenance aeration phase to minimize moisture shrink loss or other relevant criteria. Based on the airflow rate, the operator supplies a budgeted fan runtime per day, which the controller attempts to maintain. Fan operation is determined by adapting temperature and EMC bands around target values. The target temperature is the 21-day average ambient temperature and the user specifies the target moisture content. For instance, at an airflow rate of 0.1 m^3 min^{-1} t^{-1}, the budgeted runtime is 8 h/day, at 0.6 m^3 min^{-1} t^{-1} it is 0.8 h/day, and at 2.2 m^3 min^{-1} t^{-1} it is 0.2 h/day (Sentry Technologies, 1993). Under ideal conditions, the fans would run the amount specified by the budgeted runtime each day.

However, ambient conditions are often not in the ideal range to allow the fans to run for the specified amount of time per day. Based on the budgeted fan runtime per day a backlog of fan runtime is accumulated. For instance, if the airflow rate is 0.6 m^3 min^{-1} t^{-1} and the weather is not optimal to achieve the 0.8 h of runtime for that day, then the deficiency in runtime is added to the backlog. The target temperature then expands about the 21-day average temperature by 0.6°C for every 8 h of backlog. The EMC band is initially centered around the target moisture content by ±0.5% and expands by ±0.15% for every 4 h of backlog. A slight modification was made to the simulation of the Sentry PAC storage mode 1 algorithm. Excessive moisture shrink was predicted to occur due to preheating of the air across the fan and motor when the EMC of the air is calculated based solely on ambient conditions. A fan will prewarm the ambient air by approximately 0.6°C for every 250 Pa of static pressure (Hellevang, 1996). By ignoring the preheating of the air due to the motor and heat of compression, especially with large static pressures, the Sentry PAC aeration controller had a tendency to overdry the corn during maintenance aeration. As a result, the Sentry PAC storage mode 1 strategy was simulated to operate the fans based on the estimated plenum EMC as a function of the prewarming of the air by the heat of compression and fan motor.

The strategies were coded as follows: dry and cool within the dryer (DC); full heat drying followed by dryeration at the lower airflow rate (DL) and full heat drying followed by dryeration at the higher airflow rate (DH); full heat drying followed by NA in-bin drying at the lower airflow rate and a maximum moisture content of 18% (C18L), at the higher airflow rate and a maximum moisture content of 18% (C18H), at the lower airflow rate and a maximum moisture content of 17% (C17L), and at the higher airflow rate and a maximum moisture content of 17% (C17H).

IN-BIN CONDITIONING FOR EARLY HARVEST DATE IN INDIANAPOLIS, INDIANA

Table 4 presents the results for the drying and conditioning strategies for Indianapolis, Indiana, with a harvest date of 15 October for two unload dates. The DC and full heat drying followed by dryeration resulted in corn of the desired moisture content and approximately the same level of dry matter loss (DML). By optimizing the target moisture content for the modified storage mode 1 of the Sentry PAC, the desired final moisture content of 14.5% could have been reached for the respective storage end dates (not shown). Combination drying led to larger moisture shrink losses and higher dry matter losses than DC or dryeration. Dry matter losses were limited when the maximum moisture content was set to 17%. However, this resulted in an additional moisture shrink loss of 1.0 to 1.6 percentage points compared to combination drying with a maximum moisture content of 18%. The moisture shrink loss was reduced by stopping NA drying at a maximum moisture content of 18%. In all cases the DML remained below the critical 0.5% limit.

The total fan runtime was greatest when C17L was used primarily due to the NA drying stage. The fan runtime for DH was the lowest for any of the strategies investigated. Overall fan runtime and the standard deviation of the total fan runtime for DC and DH were approximately the same. With NA drying the standard deviation of the fan runtimes was much greater over the 29 years due to the variable annual weather conditions compared to DC or dryeration.

Table 4. Predicted average, range, and standard deviation of dry matter loss, moisture content, and fan runtime over 29 years at two possible unload dates within a bin in Indianapolis, Indiana, with a harvest date of 15 October

	Unload 1 January			Unload 1 July		
Strategy*	DML†	MC‡	Runtime§	DML†	MC‡	Runtime§
DC	0.06	14.8	70	0.17	14.8	199
	0.04-0.10	14.7-14.9	52-135	0.13-0.22	14.7-15.0	173-263
	0.020	0.05	19.1	0.028	0.09	20.9
DL	0.04	14.5	172	0.12	14.5	301
	0.02-0.05	14.2-14.7	154-233	0.09-0.15	14.3-14.8	275-362
	0.008	0.11	18.0	0.015	0.14	19.9
DH	0.04	14.4	102	0.12	14.5	166
	0.02-0.06	14.3-14.6	86-162	0.10-0.15	14.2-14.7	146-222
	0.008	0.09	18.3	0.014	0.13	18.7
C18L	0.09	14.3	263	0.21	14.1	304
	0.05-0.18	11.8-14.9	176-447	0.07-0.33	12.5-14.7	206-489
	0.030	0.65	59.9	0.061	0.51	60.2
C18H	0.09	14.0	191	0.26	13.9	217
	0.04-0.22	11.4-14.9	117-443	0.06-0.49	12.1-14.6	144-468
	0.036	0.96	72.6	0.113	0.66	72.6
C17L	0.06	13.1	360	0.10	13.4	400
	0.03-0.15	11.8-14.6	314-516	0.05-0.18	12.5-14.7	347-557
	0.027	0.73	71.8	0.029	0.60	41.3
C17H	0.05	12.3	289	0.08	12.8	315
	0.03-0.16	10.8-13.5	217-528	0.04-0.18	11.8-13.8	242-553
	0.025	0.707	41.143	0.031	0.60	72.0

* DC = dry and cool within dryer; DL = dryeration at low airflow rate, DH = dryeration at high airflow rate; C18L = combination drying with a maximum moisture content of 18% and low airflow rate; C18H combination drying with a maximum moisture content of 18% and high airflow rate; C17L = combination drying with a maximum moisture content of 17% and low airflow rate; C17H = combination drying with a maximum moisture content of 17% and high airflow rate.

† DML is dry matter loss in percent.

‡ MC is moisture content in percent (wet basis).

§ Fan runtime for in-bin cooling and maintenance aeration in hours.

Table 5. Predicted average, range, and standard deviation of the total drying cost ($/t) for each location and harvest date over 29 years assuming that the high drying-air temperatures were used with corn at an initial moisture content of 25% followed by storage until 1 July

Strategy*	Indianapolis HD† 15 October	Indianapolis HD† 1 November	Des Moines HD† 15 October	Des Moines HD† 1 November
DC	6.02	6.02	6.02	6.05
	5.90-6.23	5.91-6.20	5.90-6.34	5.91-6.40
	0.09	0.09	0.10	0.11
DL	5.32	5.39	5.42	5.41
	5.43-5.63	5.28-5.63	5.29-5.75	5.27-5.75
	0.08	0.09	0.10	0.13
DH	5.31	5.41	5.43	5.41
	5.46-5.62	5.30-5.62	5.28-5.71	5.28-5.67
	0.09	0.09	0.10	0.10
C18L	5.61	5.46	5.33	5.30
	4.64-7.63	4.64-6.33	4.76-6.33	4.63-8.32
	0.69	0.41	0.42	0.64
C18H	6.10	5.83	5.80	5.36
	5.01-9.22	4.97-7.53	4.90-7.89	4.61-6.70
	1.12	0.60	0.82	0.45
C17L	6.68	6.42	6.88	6.59
	5.55-8.26	5.62-7.75	5.50-8.49	5.60-8.32
	0.67	0.54	0.71	0.66
C17H	7.97	7.55	8.13	7.52
	6.43-10.73	6.49-8.74	6.18-10.15	6.39-9.55
	0.93	0.67	0.92	0.73

* See table 4 for strategy descriptions.

† HD is harvest date.

Table 5 summarizes the average costs to dry and condition corn over 29 years in Indianapolis with a harvest date of 15 October. It was assumed that corn was dried from 25% and the high-temperature dryer was operated at its maximum drying-air temperature and corn was stored until 1 July. The high-temperature drying energy costs represented approximately 90% of the total cost when DC or dryeration was used. However, this decreased to approximately 60% of the total cost when C18L and C18H were used. Combination drying was cost effective when the maximum allowable moisture to end NA drying was 18%; otherwise moisture shrink losses became too great and made combination drying uneconomical. The variability in total drying cost was greatest for combination drying and lowest for DC and dryeration. The total drying cost increased for C18H, C17L, and C17H due to the increased moisture shrink. For combination drying to be successful, moisture shrink losses that occur during NA drying have to be eliminated through the development of optimal strategies. Moisture shrink losses represented 0.53, 0.67, 1.16, and 1.81 $/t for C18L, C18H, C17L, and C17H, respectively. If drying costs for other drying-air temperatures and initial moisture contents are desired, the results from tables 3 and 5 can be combined.

IN-BIN CONDITIONING FOR LATE HARVEST DATE IN INDIANAPOLIS, INDIANA

Table 6 shows the results for Indianapolis, Indiana, with a harvest date of 1 November. By delaying harvest until 1 November the DML decreases for every drying strategy investigated because of cooler ambient conditions. The final average moisture content and range in moisture contents did not change when the harvest was delayed by two weeks for DC, DL, and DH. However, the shrink losses were not as great for the combination drying strategies. By delaying harvest for two weeks, the average final moisture content increased by 0.4, 0.3, 0.5, and 0.4 percentage points for C18L, C18H, C17L, and C17H, respectively. Utilizing the later harvest date reduced the range in the final average moisture contents for the 29 years simulated. In general, the standard deviation of the primary variables decreased by delaying harvest. The fan runtime decreased slightly by delaying harvest (less than 20 h for all strategies).

Total drying costs were reduced by 10, 9, and 3% when dryeration, C18L, and C18H, respectively, were used compared to DC (table 5). The smallest variability in total drying costs occurred for DC and dryeration, and was greatest for the combination drying strategies. By delaying harvest until 1 November, the variability in the total drying cost decreased for the combination drying strategies but remained unchanged for DC and dryeration. Delaying harvest led to a decrease in the total drying costs for combination drying, primarily due to decreased moisture shrink during the NA drying stage. Moisture shrink costs were 0.30, 0.38, 0.78, and 1.43 $/t for C18L, C18H, C17L, and C17H, respectively.

IN-BIN CONDITIONING FOR EARLY HARVEST DATE IN DES MOINES, IOWA

Results for the drying strategies in Des Moines, Iowa, using 29 years of weather data and a harvest date of 15 October are shown in table 7. Using DC and dryeration resulted in corn that had the desired final average moisture content of 14.5% and minimal DML. The DML was slightly higher for combination drying when the maximum allowable moisture content was set to 18%—including one year when the DML exceeded the maximum permissible DML of 0.5%. However, the DML for Des Moines and Indianapolis were approximately the same for each drying strategy investigated. Shrink losses were approximately the same in Des Moines and Indianapolis for the NA drying strategies simulated. When NA drying continued until the maximum moisture content within the bin was less than

Table 6. Predicted average, range, and standard deviation of dry matter loss, moisture content, and fan runtime over 29 years at two possible unload dates within a bin in Indianapolis, Indiana, with a harvest date of 1 November

	Unload 1 January			Unload 1 July		
Strategy*	DML†	MC‡	Runtime§	DML	MC‡	Runtime§
DC	0.04	14.8	52	0.15	14.8	180
	0.02-0.08	14.7-14.9	36-77	0.11-0.21	14.7-15.0	161-203
	0.015	0.04	10.2	0.021	0.08	10.1
DL	0.02	14.5	154	0.11	14.6	283
	0.01-0.03	14.4-14.7	138-179	0.09-0.14	14.4-14.8	264-305
	0.005	0.06	10.9	0.010	0.12	10.9
DH	0.02	14.5	90	0.11	14.5	154
	0.01-0.03	14.4-14.6	76-118	0.09-0.14	14.3-14.8	141-183
	0.005	0.06	10.1	0.011	0.12	9.9
C18L	0.06	14.8	279	0.19	14.5	320
	0.03-0.11	13.0-15.2	171-400	0.07-0.30	13.1-15.0	203-443
	0.019	0.42	55.2	0.050	0.40	55.7
C18H	0.06	14.5	195	0.24	14.2	222
	0.03-0.14	13.0-15.0	116-317	0.05-0.44	12.9-14.8	125-345
	0.026	0.50	46.1	0.099	0.45	48.5
C17L	0.05	13.8	381	0.11	13.9	422
	0.02-0.09	11.9-15.1	290-460	0.05-0.22	12.2-15.0	326-504
	0.018	0.84	38.3	0.043	0.71	39.7
C17H	0.04	12.9	283	0.08	13.2	310
	0.02-0.11	11.3-13.8	227-418	0.03-0.15	11.6-14.0	237-446
	0.022	0.71	45.0	0.029	0.59	46.2

* See table 4 for strategy descriptions.
† DML is dry matter loss in percent.
‡ MC is moisture content in percent (wet basis).
§ Fan runtime for in-bin cooling and maintenance aeration in hours.

Table 7. Predicted average, range, and standard deviation of dry matter loss, moisture content, and fan runtime over 29 years at two possible unload dates within a bin in Des Moines, Iowa, with a harvest date of 15 October

	Unload 1 January			Unload 1 July		
Strategy*	DML†	MC‡	Runtime§	DML	MC‡	Runtime§
DC	0.05	14.8	64	0.15	14.8	199
	0.03-0.09	14.7-14.9	37-144	0.11-0.18	14.7-15.1	174-276
	0.016	0.04	20.7	0.018	0.09	19.7
DL	0.03	14.4	163	0.11	14.5	299
	0.02-0.05	14.3-14.6	138-200	0.08-0.13	14.3-14.9	276-338
	0.007	0.09	13.8	0.012	0.14	12.5
DH	0.03	14.4	97	0.04	14.4	135
	0.02-0.06	14.3-14.6	79-178	0.03-0.07	14.2-14.7	120-219
	0.008	0.09	18.9	0.008	0.12	18.8
C18L	0.09	14.5	236	0.23	14.2	277
	0.04-0.21	13.3-14.9	164-364	0.10-0.46	13.2-14.9	204-409
	0.033	0.39	53.7	0.079	0.39	54.9
C18H	0.09	14.2	172	0.26	14.0	197
	0.04-0.23	11.9-15.0	114-337	0.07-0.50	12.2-14.6	129-371
	0.035	0.66	57.0	0.114	0.54	59.1
C17L	0.05	12.7	351	0.09	13.2	392
	0.02-0.13	11.0-14.3	300-502	0.03-0.19	12.0-14.5	332-547
	0.027	0.83	45.2	0.035	0.65	46.4
C17H	0.04	12.0	274	0.06	12.5	299
	0.02-0.14	10.3-14.0	219-432	0.03-0.15	11.4-14.2	243-466
	0.027	0.94	53.8	0.031	0.77	55.6

* See table 4 for strategy descriptions.
† DML is dry matter loss in percent.
‡ MC is moisture content in percent (wet basis).
§ Fan runtime for in-bin cooling and maintenance aeration in hours.

17%, the corn had significantly overdried before the automatic fan controller went into the storage mode. The controller generally reconditioned the moisture content upwards during the storage mode. Approximately 0.5 percentage points of moisture were gained by extending the storage season from 1 January to 1 July at the low maximum moisture content limits. Also, the airflow rate of 1.7 m^3 min^{-1} t^{-1} did not overdry the corn as severely as the airflow rate of 2.2 m^3 min^{-1} t^{-1}. This indicates that the Sentry PAC was effective in conditioning the corn during the storage period. When the fans were operated continuously until the maximum moisture content was less than 18%, overdying was limited. However, there was a slight increase in DML when combination drying was used compared to DC and dryeration if corn was stored until 1 July.

Fan runtime was greatest for combination drying when the maximum allowable moisture content was 17%, requiring on average 392 and 299 h when storing corn until 1 July with airflow rates of 1.7 and 2.2 m^3 min^{-1} t^{-1}, respectively. However, if DC and DH were used, the average fan runtime was 199 and 135 h when storing corn with those airflow rates until 1 July, respectively. The standard deviations of the fan runtimes were approximately the same for all combination drying strategies, 46 to 59 h/year when stored until 1 July. The DC and dryeration processes showed considerably less variation than combination drying since the standard deviations of the fan runtimes were much smaller.

The total costs for drying and storing corn until 1 July with the different strategies is given in table 5. By utilizing dryeration rather than DC, the total cost of drying 25% moisture corn was reduced by approximately 10%. When C18L was used, the high-temperature dryer represented 62% of the total cost of drying. The cost due to fan operation represented 28%, shrink 7%, fan operation 28%, and DML 3% of the total drying cost. When the maximum allowable moisture content during NA drying was 17%, combination drying became uneconomical compared to DC, dryeration, and combination drying with a maximum moisture content of 18%, primarily due to the excessive shrink loss and fan runtime. DML represented a relatively small percentage of the total drying cost for any of the drying strategies; cost of DML was between 0.5 and 3.6% of the total cost.

IN-BIN CONDITIONING FOR LATE HARVEST DATE IN DES MOINES, IOWA

Table 8 shows the results for Des Moines, Iowa, with a harvest date of 1 November. Results were similar to those for Indianapolis: delaying harvest until 1 November decreased DML for every drying strategy investigated and the average moisture contents using DC, DL, and DH were approximately 14.5%. With the combination drying strategies, shrink losses were reduced by 0.3 to 0.5 percentage points with a maximum moisture content of 18%, and by 0.5 to 0.8 percentage points with a maximum moisture content of 17% compared to the earlier harvest date. Over 29 years, the range in the final moisture contents was generally reduced and the standard deviation of the primary variables generally decreased by delaying harvest. The fan runtime decreased by 5 to 20 h for DC, DL, C18L and C17H, and increased by 25 to 28 h for C17L and C18L, while for DH it decreased for the early unload date, but increased for the late unload date.

Table 8. Predicted average, range, and standard deviation of dry matter loss, moisture content, and fan runtime over 29 years at two possible unload dates within a bin in Des Moines, Iowa, with a harvest date of 1 November

	Unload 1 January			Unload 1 July		
Strategy*	DML†	MC‡	Runtime§	DML	MC‡	Runtime§
DC	0.04	14.8	44	0.13	14.9	179
	0.02-0.07	14.7-15.0	24-55	0.10-0.17	14.7-15.2	161-192
	0.012	0.06	9.0	0.018	0.09	7.2
DL	0.02	14.5	144	0.10	14.6	281
	0.01-0.03	14.4-14.7	119-157	0.08-0.12	14.4-14.9	263-294
	0.005	0.07	10.9	0.010	0.13	7.2
DH	0.02	14.5	83	0.10	14.6	150
	0.01-0.03	14.4-14.7	70-100	0.08-0.13	14.4-14.9	134-158
	0.004	0.06	6.6	0.011	0.11	5.2
C18L	0.05	14.8	264	0.19	14.6	305
	0.03-0.09	14.3-15.4	168-698	0.12-0.37	14.1-15.3	207-745
	0.016	0.20	91.2	0.049	0.26	93.6
C18H	0.04	14.7	161	0.12	14.3	192
	0.02-0.07	13.7-15.1	98-229	0.06-0.19	13.4-14.8	127-263
	0.015	0.30	32.4	0.029	0.29	32.6
C17L	0.04	13.5	377	0.09	13.7	418
	0.02-0.07	11.5-15.4	299-691	0.04-0.20	12.2-15.3	337-745
	0.014	0.91	67.4	0.037	0.76	69.8
C17H	0.03	12.6	258	0.06	13.0	283
	0.02-0.06	10.6-14.2	214-316	0.02-0.11	11.1-14.3	237-342
	0.013	0.83	23.7	0.021	0.74	24.0

* See table 4 for strategy descriptions.
† DML is dry matter loss in percent.
‡ MC is moisture content in percent (wet basis).
§ Fan runtime for in-bin cooling and maintenance aeration in hours.

Total drying costs were reduced by 11, 12, and 11% when dryeration, C18L, and C18H, respectively, were used compared to DC (table 5) due to lower moisture shrink losses. However, drying costs increased for C17L and C17H. By delaying the harvest in Des Moines, the variability of the total drying costs decreased for C18H, C17L and C17H, but increased for C18L, while variability remained essentially unchanged for DC and dryeration.

DISCUSSION

Average drying costs across locations and harvest dates for corn with an initial moisture content of 25% were 6.03 $/t for DC, 5.39 $/t for dryeration, and 5.43, 5.77, 6.64, and 7.79 $/t for C18L, C18H, C17L, and C17H, respectively (table 5). A number of factors affect the decision of what drying technique is optimal for a given farm (or elevator). If a farm is looking to significantly increase dryer capacity and has natural-air drying bins already available, then combination drying appears to be an economically feasible alternative despite increased risk and variability. Natural-air drying can be more difficult to control and more challenging to manage. To make combination drying a cost-effective alternative to dryeration or DC, the shrink loss that is predicted to occur during the extended conditioning period has to be eliminated or minimized.

For DC and dryeration, the important variables (DML, average moisture content, and fan runtime) had relatively small standard deviations. However, when combination drying was used, the standard deviations for all three variables increased, especially the standard deviation of the final average moisture content. For instance, if corn was stored until 1 July, the standard deviation of the average moisture content with DC was 0.09% compared to 0.39% for C18L at both locations and harvest dates.

Some of the shrink loss that occurred could be prevented or minimized by optimizing NA drying or use of the aeration controller during storage. However, optimization of NA drying and aeration control were beyond the scope of this project.

Combination drying could become even more economically feasible if the price of LP gas increased, which would shift the advantage to NA in-bin drying, or if premiums were paid to farmers for low stress crack corn. For example, if corn was dried from 25% on 15 October in Indianapolis and the price of LP gas was increased from 0.185 to 0.343 $/L and the electrical energy price remained constant at 0.07 $/kWh, dryeration and combination drying would become even more economically attractive compared to conventional DC (table 9). The increase in LP gas cost resulted in combination drying (C18L) having 20 and 12% lower total drying costs than DC and dryeration, respectively. If the moisture shrink loss could be eliminated by more efficient NA drying techniques, the total cost of combination drying would be 25% lower than for DC. This indicates that additional research needs to focus on optimal NA drying strategies that limit moisture shrink.

Table 10 presents the overall energy use of the drying and storage strategies investigated. For all practical purposes, energy use values for each strategy are identical for each location and harvest date. However, when compared to DC, energy use decreased by approximately 8 and 28% when dryeration and combination drying were used, respectively.

Other factors when considering dryeration or combination drying over conventional DC are the potential test weight gain and possible premiums for corn with low stress crack percentages. Both of these factors could make dryeration and combination drying even more cost effective compared to DC. However, dryeration requires more handling and management to prevent condensation than traditional DC. NA drying requires an even greater amount of management than DC or dryeration, a sufficient number of bins equipped with NA drying systems, and an automatic fan controller that is optimized to achieve the desired least cost, maximum quality results.

Table 9. Total cost of drying and conditioning in Indianapolis, Indiana, with a harvest date of 15 October and storage until 1 July, using the high drying-air temperatures and an initial moisture content of 25% with a gas cost of 0.185 $/L or 0.343 $/L and an electricity cost of 0.07 $/kWh

		0.185 $/L, 0.07 $/kWh		0.343 $/L, 0.07 $/kWh	
Strategy*	Shrink Cost ($/t)	Crossflow Drying Cost ($/t)	Total Cost ($/t)	Crossflow Drying Cost ($/t)	Total Cost ($/t)
DC	0.32	5.39	5.97	6.77	7.35
DL	0.12	4.94	5.43	6.27	6.67
DH	0.12	4.94	5.46	6.27	6.69
C18L	0.53	3.29	5.61	4.17	6.03
C18H	0.67	3.29	6.10	4.17	6.43
C17L	1.16	3.29	6.68	4.17	6.95
C17H	1.81	3.29	7.97	4.17	8.05

* See table 4 for strategy descriptions.

Table 10. Overall energy use (kJ/kg of water removed)* of the drying and storage strategies using the high drying-air temperatures and an initial harvest moisture content of 25% and storage until 1 July

Strategy†	Indianapolis HD‡ 15 October	Indianapolis HD‡ 1 November	Des Moines HD‡ 15 October	Des Moines HD‡ 1 November
DC	4850	4840	4845	4840
DL	4430	4460	4465	4460
DH	4440	4430	4420	4430
C18L	3370	3510	3425	3480
C18H	3425	3520	3440	3425
C17L	3220	3535	3480	3530
C17H	3590	3520	3490	3440

* kJ/kg water removed = LP gas and electrical energy used by the crossflow dryer divided by water removed while corn was in the dryer and during in-bin cooling and NA drying.

† See table 4 for strategy descriptions.

‡ HD is harvest date.

CONCLUSIONS

The following conclusions are based on the simulated investigation of drying and cooling within the dryer, full heat drying followed by dryeration, and full heat drying followed by natural-air drying for Des Moines, Iowa, and Indianapolis, Indiana.

1. Combination drying and dryeration increased drying capacity by 72 and 159% compared to conventional drying and cooling within the dryer, respectively. Combination drying for both locations, harvest moistures, and harvest dates used approximately 22% less energy than dryeration and 28% less energy than drying and cooling within the dryer. Total drying costs were about 11% lower for dryeration and combination drying relative to conventional drying and cooling within the dryer when current energy costs were considered. If moisture shrink losses were minimized during in-bin conditioning, combination drying would be the least cost strategy for any harvest date, harvest moisture content, and location, especially if gas costs increased.
2. There was little difference in total drying and conditioning costs between Des Moines, Iowa, and Indianapolis, Indiana, for the same harvest moistures and dates when comparing conventional drying and cooling within the dryer and full heat crossflow drying followed by dryeration. However, a later harvest date of 1 November compared to 15 October decreased the natural-air drying costs at both locations by up to 5%.
3. From an overall cost-benefit perspective, designing a grain drying and storage system with a full heat dryer followed by dryeration in a bin equipped with a fan to deliver 1.1 $m^3 min^{-1} t^{-1}$ appears most desirable. In case energy costs increased, such a system could be adapted to transferring corn hot at 20% moisture content, followed by tempering, in-bin cooling, drying with natural-air, and conditioning utilizing an automatic fan controller with a modified adaptive equilibrium moisture content strategy that minimizes shrink loss.

ACKNOWLEDGMENTS. The authors thank Mr. Dan Kallestad (Sentry Technologies, Chico, California) for donating two Sentry PAC fan controllers for the field tests. The authors thank Mr. Curt Fankhauser (Farm Fans, Indianapolis, Indiana) for donating a FFI C2125A high temperature dryer for this project. The financial support of Hoosier Energy (Bloomington, Indiana) and Wabash Power (Indianapolis, Indiana) is acknowledged. The assistance of Mr. Jim Beaty and Mr. Jeff Fields (Purdue University Agronomy Research Center) in conducting the multi-year drying studies was much appreciated.

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NOMENCLATURE

C17L	Combination drying until a maximum moisture content of 18% was reached at an airflow rate of 1.7 $m^3\ min^{-1}\ t^{-1}$.
C17H	Combination drying until a maximum moisture content of 18% was reached at an airflow rate of 2.2 $m^3\ min^{-1}\ t^{-1}$.
C18L	Combination drying until a maximum moisture content of 18% was reached at an airflow rate of 1.7 $m^3\ min^{-1}\ t^{-1}$.
C18H	Combination drying until a maximum moisture content of 18% was reached at an airflow rate of 2.2 $m^3\ min^{-1}\ t^{-1}$.
DC	Dry and cool within the dryer.
DL	Dryeration at an airflow rate of 0.6 $m^3\ min^{-1}\ t^{-1}$.
DH	Dryeration at an airflow rate of 1.0 $m^3\ min^{-1}\ t^{-1}$.
DML	Percent dry matter loss.
MC	Moisture content % wet basis.
HD	Harvest date.
NA	Natural-air drying.