Moisture Changes During Aeration of Grain

George H. Foster
Member ASAE

THE practice of aerating stored grain was established during the 1950s and is now an accepted quality-maintenance measure. The aeration development was coincident with the build-up of reserve stocks of grain following World War II. Large flat storages were used to hold much of the reserve grain, and aeration was first developed for this type of storage. The experience with aeration in flat storages was so favorable that the practice was soon adapted to silos and upright storages at grain elevators and to larger farm-type grain bins.

This paper discusses the theoretical basis for moisture exchanges between the grain and the cooling air in aeration, and reports in part on laboratory aeration tests with wheat and on field tests of cooling hot corn from a heated-air drier with aeration.

Uses of Aeration

The small amount of air forced through the grain in aeration prevents large temperature differences from developing within the grain mass from seasonal temperature changes. This prevents moisture from migrating from warmer grain and accumulating in damaging amounts in the cooler grain within the storage. This was the first use of aeration and is the most widespread. Aeration is also used to maintain grain at lower than the average outdoor air temperatures by aerating during "cold snaps."

Two other uses of aeration have developed during the past three years. The practice of holding wet grain through the winter months with aeration is growing in the Corn Belt. Corn at 18 to 22 percent moisture has been held from harvest until warm weather the following spring. The use of aeration for holding wet grain for shorter periods of time until it can be dried is even more widespread.

Aeration is also being used to cool corn and other grain after heat drying. This method of cooling is used with the dryeration (1)* process that is being rapidly adopted for high-speed drying of field-shelled corn.

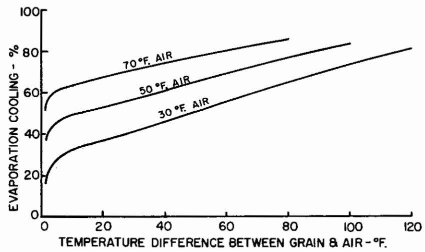

FIG. 1 Percent of total cooling attributed to moisture evaporation during aeration.

Observed Grain Moisture Losses During Aeration Cooling

Most grain-storage operators have experienced moisture loss in grain cooled by aeration. When grain is stored for more than one season and aeration is used to cool the grain each fall, the accumulated moisture loss may exceed one percentage point. Moisture losses attributed to aeration are usually between one-half and one percent.

Wheat aeration tests in Kansas, reported by Kline and Converse (2), resulted in a moisture reduction of 0.6 percent when the wheat was cooled from 95 to 50 F. The drying accompanying a 15 F wheat-temperature reduction in the summer was three times that for a 15 F temperature reduction during the winter. The cooling effect of the moisture evaporated was demonstrated by the difference in the aeration time required in the summer and in the winter. With 0.3 percent moisture removal in the summer, 160 hr was required to cool the wheat 15 F. The moisture reduction during the winter aeration was 0.1 percent and 310 hr was required to effect the same temperature reduction.

Theoretical Considerations in Aeration

It is impossible to cool grain more than a few degrees by aeration without reducing its moisture content. For example, if saturated air at 50 F is warmed 10 F or more when passing through 14 percent corn, it will have a net drying effect. Conversely, warming cool grain by passing air through it will normally increase its moisture content.

It is helpful in understanding the aeration process, if one considers first the ideal situation where the cooling air entering the grain is warmed to the initial grain temperature before it is exhausted. With airflow rates normally used for aeration, this condition prevails during the first part of the cooling period. In the ideal situation, the cooling zone is of negligible thickness and the maximum temperature change in the cooling air occurs throughout the cooling period. The temperature rise in the air is equal to the temperature drop in the grain.

When a heat-balance equation is written for the ideal case, the two temperature terms are equal and drop out. The amount of air required to cool grain then is simply a ratio of the specific heat of the grain to the specific heat of the air. If the specific heats of grain and air are 0.4 and 0.24 Btu per pound per deg F., respectively, 1⅔ lb of air is required to cool each pound of grain. Translating this to commonly used terms of cubic feet of air and bushels of grain, the requirement is about 1300 cu ft of air for each 60-lb bushel. If the air is supplied at a rate of 0.1 cu ft per min (cfm) per bu, then the cooling time required is about 220 hr. This considers only sensible heat exchange and does not include the evaporative cooling effect of the latent heat exchange incident to the cooling process.

Continuing with the ideal case, and considering both sensible and latent heat, the importance of the moisture changes during aeration becomes apparent. Here it is assumed that the aeration air is exhausted in both temperature and moisture equilibrium with the warm grain. To raise the temperature of the air and maintain or increase the relative humidity, the absolute humidity (pounds of water per pound of air) must be increased. In aeration the increase must come from moisture removed from the grain. Furthermore, the grain must supply the heat for evaporating the moisture. Thus, the moisture removal incident to cooling reduces the amount of sensible heat exchange required and lowers the quantity of cooling air required to effect a given temperature change in the grain.

For example, consider cooling wheat at 80 F with cooling air entering at 50 F and 60 percent relative humidity in

Paper No. 65-921 presented at the Winter Meeting of the American Society of Agricultural Engineers at Chicago, Ill., December 1965, on a program arranged by the Farm Structures Division.

The author—GEORGE H. FOSTER—is agricultural engineer, ARS, USDA, Lafayette, Ind.

* Numbers in parentheses refer to the appended references.

Author's Note: This paper reports a research study conducted by the Transportation and Facilities Research Division, ARS, USDA, in co-operation with Purdue University agricultural experiment station, and is designated as Purdue AES journal paper No. 2893. The author gratefully acknowledges contributions to the study reported by the following USDA agricultural engineers: B. M. Stahl, who developed laboratory aeration equipment and conducted the initial tests; E. F. Willms, who completed the laboratory tests and summarized much of the data; and R. A. Thompson, who assisted in the field aeration tests with hot corn.

This article is reprinted from the Transactions of the ASAE (vol. 10, no. 3, pp. 344, 345, 346, 347 and 351, 1967), the Transactions of the American Society of Agricultural Engineers, Saint Joseph, Michigan

equilibrium with 12 percent wheat. Assume that the air exhausts from the wheat at the same relative humidity. The heat content of the air is increased 16.8 Btu per lb rather than 7.2 Btu per lb where only sensible heat change was considered. With the evaporative cooling from the latent heat exchange, the quantity of cooling air required per pound of grain is reduced from 1.67 to 0.714. This is a reduction of 57.2 percent.

The percent of the total cooling attributable to evaporation increases as the difference between the grain temperature and the cooling-air temperature increases. For the same temperature difference, it also is greater at higher cooling air temperatures. These relationships are shown in Fig. 1.

Moisture Reduction During Cooling

The amount of moisture reduction incident to the cooling process can be calculated for the ideal case. Continuing with the example of cooling 80 F wheat with 50 F air, psychrometric data show that 60.5 grains of moisture is removed with each pound of cooling air. Since 0.714 lb of air was required to cool each pound of grain, the amount of moisture removed reduces the moisture content of the wheat from 12 to 11.45 percent. Examples of the theoretical maximum amount of moisture reduction possible when cooling grain are given in Table 1.

Aeration with High or Low Humidity Air

The effect of aerating with air at relative humidities not in equilibrium with the grain is considered in the following example of cooling 12 percent grain from 80 F with air at 50 F and 100 percent relative humidity. Upon entering the grain, the saturated air gives up moisture to the grain until equilibrium is approached. If this process proceeds adiabatically, the heat of condensation from the moisture added to the grain warms the air to 57 F. The grain between the cooling zone and the slower moving wetting zone cannot be cooled to below 57 F. Only that grain near where the air enters, that has reached a moisture content in equilibrium with the saturated air, will be cooled to the entering air temperature of 50 F. Thus the amount of temperature reduction possible with the saturated air is less than that with air

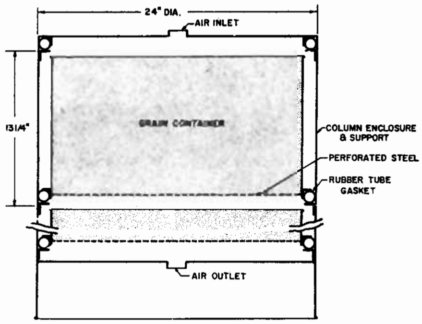

FIG. 2 Sectional view of steel grain column used in laboratory aeration tests.

in moisture equilibrium with the grain.

In the example, the difference between the enthalpy of the air entering and leaving the grain is 13.5 Btu per lb. The heat removal required to lower the grain temperature from 80 to 57 F is 9.2 Btu per lb. The cooling air required is 0.681 lb per lb of grain. The moisture content of the grain is reduced by 0.34 percent, about one half that in the previous example with cooling air at 60 percent relative humidity.

Water was added to the grain near where the air entered at the rate of 11.5 grains per pound of air and taken out of the grain beyond that point at a rate of 50.5 grains per lb of air. The difference is the net moisture removal of 39.0 grains per lb of air, which accounts for the grain moisture reduction of 0.34 percent.

Aerating with cooling air at relative humidities lower than those in equilibrium with the grain results in increased temperature reduction and moisture removal.

Laboratory Aeration Tests

Laboratory aeration tests were conducted from 1960 to 1962 to determine how closely actual results approached the theoretical results under ideal conditions.

Equipment and Methods

The tests were conducted with 10 bu of wheat contained in a steel column 5 ft deep. The column was made up of five baskets 1 ft deep, each resting on a rubber tube supported on an outer shell (Fig. 2). Air was pulled through the column, metered through a rotameter and discharged through a rotary blower (Fig. 3). The temperature was recorded at the air inlet, between each 1-ft layer of grain, and at the air exhaust. The temperature was also recorded 3 in. below the top wheat surface and 3 in. above the bottom of the wheat in each basket. The dewpoint of the entering and exhaust air was recorded, along with the relative humidity between each 1-ft layer of grain.

For the 1961-62 tests, the entire grain column was placed on a platform scale for direct measurement of the weight changes during aeration. The grain column was insulated with 18 in. of glass fiber.

Most of the tests were made with the grain column inside a controlled-climate room where both temperature and humidity were maintained at the desired level. The procedure for a cooling test was essentially as follows: The temperature and relative humidity of the air in the controlled-climate room were set to bring the wheat to the initial temperature and moisture content desired for a test. The wheat was then aerated until it reached temperature and moisture equilibrium with the room air. The air conditions in the controlled climate room were then changed to the desired level for cooling. The air surrounding the test column was then pulled through the grain. This simulated normal aeration practice where outdoor air is used to cool grain. After cooling was completed, the air temperature in the room was raised to the desired level and a warming test conducted.

Consideration was given to the effect of conductive heat losses or gains on the test results. Regardless of the amount of insulation used, satisfactory test results could not be obtained at airflows less than about 0.2 cfm per bu of wheat.

The effect of conductive heat losses was evaluated for cooling tests by moving the column outside the controlled-temperature room to an area where it was surrounded by air at approximately the initial grain temperature rather than the cooling-air temperature. The cooling air was drawn from the controlled-temperature room. In this way the column was subject to a heat gain from its surroundings rather than to a heat loss. The cooling time at an airflow rate of 0.5 cfm per bu was within 10 percent of that required with the column surrounded by the cooling air.

Another factor affecting the results of laboratory tests was the high ratio of container weight to wheat weight. The steel in the column weighed nearly one-half that of the wheat. The steel, together with the tubes used for air seals between the sections, had a total heat capacity equal to about 2 bu of wheat. Since the column was within the insulation, it was assumed that the change in temperature of the steel approached that of the wheat. However, the conductive heat losses from the col-

TABLE 1. MAXIMUM MOISTURE REMOVAL WHEN COOLING 12 PERCENT GRAIN

Grain temperature, deg F	Cooling air temperature,* deg F	Air required per pound grain, lb	Moisture removed per pound of air, lb	Grain moisture reduction during cooling, percent
150	50	0.28	0.104	2.64
125	50	0.41	0.049	1.82
100	50	0.57	0.021	1.06
75	50	0.76	0.0067	0.46
50	25	1.11	0.0027	0.28

* Air is assumed to enter at 60 percent relative humidity in moisture equilibrium with 12 percent grain, and to exhaust at the same relative humidity.

umn during the cooling tests served to reduce the effect of the extra heat capacity of the steel. Similarly, heat leakage into the test column during warming tests served to warm the steel. Thus, the error from conductive heat losses or gains and the error associated with the heat capacity of the steel column were partially offsetting. The total estimated error in the laboratory tests reported was 10 percent or under.

One of the procedural problems involved in analyzing the results of the laboratory tests was determining when the grain was cool. Theoretically, the time required to cool the grain exactly to air temperature is infinite. As the cooling zone moves out of the wheat, the rate of heat removal drops and the cooling time is increased proportionately. In these tests the wheat was considered cooled when the exhaust layer had cooled two-thirds of the way from its initial temperature to the cooling-air temperature. At this point, between 85 and 90 percent of possible cooling had been completed.

Laboratory Test Results

The results presented are based primarily on the last series of tests conducted in 1961 and 1962. Eight cooling tests are summarized in Table 2. The cooling time ranged from 17½ hr at an airflow rate of 0.8 cfm to 48 hr at an airflow rate of 0.2 cfm. The cooling time for the six tests at the 0.5 cfm per bu airflow rate averaged 23 hrs. The 23 hr at 0.5 cfm per bu is equivalent to 0.87 lb of cooling air per lb and compares to the theoretical requirement of 0.714 lb calculated for the ideal case. The airflow requirement in the tests was 25 percent greater than expected under ideal conditions. It should be remembered that only about 90 percent of the theoretical maximum temperature reduction was accomplished. The cooling from evaporation of moisture from the wheat was 54 percent of the total, which compares to the 57.2 percent predicted under ideal conditions. The moisture loss in terms of percentage points ranged from 0.4 to 0.6 percent. As developed earlier, the moisture loss under ideal cooling conditions was 0.55 percent where 12 percent grain is cooled from 80 to 50 F. In those tests in Table 2 where the air entered in equilibrium with the cooled grain, as was assumed in the ideal case, the moisture loss varied from 0.4 to 0.5 percent, or about 20 percent less than predicted.

The data presented in Table 2 show that the time required to cool the wheat was about inversely proportional to the airflow rate. The cooling efficiency in the test at the low airflow rate seems to be somewhat higher, but this may be accounted for by the longer cooling time and the greater conductive heat losses from the test column.

TABLE 2. SUMMARY OF LABORATORY WHEAT COOLING TESTS

Airflow rate, per bu	Cooling air		Wheat temperature		Aeration time,† hr	Grain moisture reduction, percent	Cooling from moisture evaporation, percent of total
	Temp, deg F	RH,* percent	Initial, deg F	Final,† deg F			
0.5‡	50	E	79.4	54.2	26	0.4	48
0.5	50	E	79.3	53.6	22	0.5	57
0.5‡	50	E−10	79.5	52.3	22	0.5	57
0.5	50	E−20	79.0	51.6	21	0.6	62
0.5‡	50	E+10	80.9	54.4	24	0.4	50
0.5	50	E+20	80.0	56.7	24	0.4	50
0.2	50	E	80.0	54.2	48	0.4	55
0.8‡	50	E	80.0	54.1	17½	0.4	46

* Relative humidity of intake air: E indicates RH in moisture equilibrium with the cooled wheat.
† The tests were stopped when the wheat nearest the air exhaust was two-thirds cooled.
‡ The moisture content of the wheat used in these tests was about 11.5 percent; in the other tests the wheat moisture was about 13.5 percent.

TABLE 3. RESULTS OF THREE-STAGE COOLING OF WHEAT IN STEPS OF 15 F

Wheat temperature reduction, deg F	Cooling air temperature, deg F	Aeration time, hr*	Grain moisture reduction		Cooling from moisture evaporation, percent of total
			Lb	Percent	
95 to 80	80	13.5	2.7	0.4	77
80 to 65	65	18.5	1.9	0.3	62
65 to 50	50	24.0	1.4	0.2	49

* Cooling in each stage was stopped when the wheat nearest the exhaust was within 5 F of the cooling air temperature.

The effect of entering air relative humidity is shown by the results of four of the tests listed in Table 2 and by the test results illustrated in Fig. 4. When the relative humidity of the input air was reduced 20 percent below that in equilibrium with the grain, the moisture reduction was 0.6 percent, equivalent to that under ideal conditions with air at equilibrium. The amount of cooling from moisture evaporation increased and the wheat was cooled to below the temperature of the entering air.

When the input relative humidity was increased above equilibrium, the cooling time and the moisture loss were changed little from those where the air entered in equilibrium. The most significant result was the inability of higher humidity cooling air to cool the bulk of the grain to the cooling air temperature.

The moisture removal when the entering relative humidity was below equilibrium was greatest in the wheat near where the air entered. When the relative humidity was above equilibrium, the moisture reduction was lowest where the air entered. For example, the moisture loss was 0.35 pound in the first foot of wheat when the entering air was 10 percent above equilibrium. When the entering air was 10 percent below equilibrium, the weight loss in the first foot of wheat was 1.0 pound.

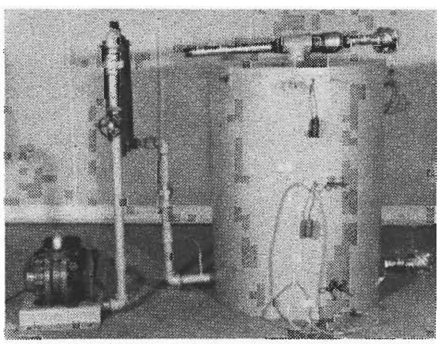

FIG. 3 Two of five sections of laboratory grain column assembled without insulation and showing apparatus for moving and measuring amount and condition aeration air.

The moisture loss data presented in Table 2 were calculated from the difference in absolute humidity of the air entering and leaving the wheat.

Three-Stage Cooling Test

One test conducted in the laboratory simulated the multistage cooling of wheat practiced in the Central Plains. The temperature of the wheat was reduced from 95 to 50 F, in three steps of 15 F, using cooling air temperatures of 80, 65, and finally, 50 F. An airflow rate of 0.5 cfm per bushel was used. The results of this test are presented in Table 3. The cooling time for each stage increased and the moisture removed decreased in successive steps as the temperature was lowered. The moisture removed was slightly higher, but in the same order as the moisture reductions reported (2) for cooling wheat in 15 F steps at Kansas elevators by successive aeration periods in the summer, fall and winter. The percentage of the cooling represented by the moisture evaporation checks well with that in Fig. 1.

The results of the final two stages of the three-stage cooling tests, taken together, compare favorably with the two single-stage tests presented first in Table 2. In both cases, the wheat was cooled from 80 to 50 F. The moisture removed in the two stages was 3.3 lb as compared to 3.1 lb when the cooling was done in one stage. For the two stages, 42.5 hr of total cooling time was required, compared to 22 hr for the single-stage. The time required to complete a cooling stage is largely independent of the temperature reduction made, except for differences in the amount of moisture removal.

More Moisture Added During Warming

Most of the laboratory cooling tests were followed by tests where the wheat was warmed by aeration to its original temperature before beginning the next cooling test. Less aeration time was required for warming than for cooling, and more moisture was regained by the wheat than had been lost during cooling. Table 4 shows the moisture changes in three pairs of tests where the wheat was first cooled from 80 to 50 F and then warmed the same amount. In these tests, aeration was continued until the wheat temperature was within 1 F of the air temperature. The first test listed was with wheat at about 11 percent moisture, while the last two tests were with wheat at about 13.5 percent moisture. An average of 3.1 lb of moisture was lost during cooling, while 3.8 lb of moisture was added during warming. This represented an average wheat moisture reduction of 0.47 percent cooling and an average increase of 0.58 percent during warming.

The reason for the difference in the amount of moisture transfer during warming and during cooling was not precisely established. Examination of the temperature and relative humidity of the air at intermediate points during the tests indicated that the potential for wetting during warming was greater than the potential for drying during cooling.

TABLE 4. COMPARISON OF WHEAT MOISTURE CHANGES DURING COOLING AND WARMING BETWEEN 50 AND 80 F

Test numbers	Moisture reduction during cooling		Moisture gain during warming	
	Lb	Percent	Lb	Percent
C8 & W8	2.9	0.46	3.9	0.67
C5 & W5	3.4	0.52	4.0	0.57
C2 & W3	3.1	0.44	3.5	0.50

Cooling Hot Corn from a Drier with Aeration

One of the features of the dryeration process (2) recently developed for drying field-shelled corn is the aeration cooling of the hot corn. In this process, hot corn is removed from the drier at a moisture level two to three percentage points above the desired final level, accumulated in a storage bin equipped for aeration, allowed to temper for a few hours, and then cooled slowly by aeration. This process not only improves the quality of the artificially dried corn but permits increased capacity with conventional batch and continuous-flow driers.

Hot corn aeration tests were conducted at an experimental drying facility located on the Purdue University agronomy farm. Corn was field-shelled at 25 percent moisture content and

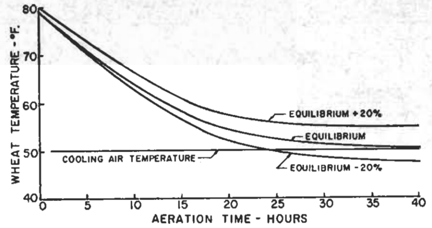

FIG. 4 Effect on final grain temperature of using cooling air with a relative humidity not in equilibrium with the grain.

dried to about 16 percent moisture in a continuous-flow, tower-type drier. The corn was moved out of the drier without cooling and accumulated in small steel storage bins in lots of 300 to 400 bu. After the hot corn had tempered for a few hours, it was cooled by aeration with an airflow rate of approximately 0.5 cfm per bu.

The moisture content of the corn was determined from samples taken as the tempering bin was loaded and again as the bin was emptied after aeration. The temperature of the corn was recorded at 20-min intervals during the test using a system of thermocouples in the bin.

The temperature reduction during a typical test of cooling hot corn by aeration is shown in Fig. 5. With an airflow rate of 0.5 cfm per bushel, the corn was cooled from 130 to an average of 65 F in about 12 hr. The cooling was done overnight. The temperature in the top foot of corn stayed at or above the initial average grain temperature for about the first four hours of the test. During this time the moisture removal and cooling rate were at a maximum. The top foot of grain then began to cool. The rate of heat removal dropped and the aeration time required was lengthened accordingly. However, the amount of moisture removed from the corn was only slightly less than in the ideal case where air exhausts at the initial grain temperature for the total (but correspondingly shorter) cooling period.

The corn moisture reduction observed during tests of cooling hot corn by aeration is shown in Table 5. There were six tests at each of the three corn temperature levels. The average moisture removal in these tests nearly equaled the theoretical maximum amounts shown in Table 1.

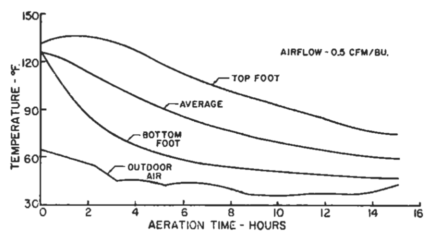

FIG. 5 Temperatures during a typical test of cooling hot corn by aeration.

TABLE 5. CORN MOISTURE REDUCTION IN TESTS OF COOLING HOT CORN BY AERATION

Corn temperature, deg F	Moisture reduction, percent	
	Average	Range
128	1.7	1.5 to 1.9
142	2.1	1.7 to 2.3
152	2.5	2.0 to 3.1

The relatively large amount of moisture removal that can be accomplished during cooling of hot corn is the key to the successful application of the dryeration process. If no moisture were removed, about 1300 cu ft of air would be needed to cool each bushel of corn. With two percentage points moisture removal, the volume of air needed is reduced to 400 cu ft per bushel. This brings the airflow rate and cooling time within practical limits for farm and elevator applications. For example, at a rate of 0.5 cfm per bu, it requires only 13.3 hr to supply 400 cu ft of cooling air to each bushel. In these tests, the cooling time varied from 10 to 14 hrs.

TABLE 6. COMPARISON OF WATER-REMOVAL CAPACITY OF AIR IN THREE DIFFERENT DRYING SITUATIONS

Starting with air at 70 F, 70 percent RH and:	Water removal capacity Pounds per 10,000 cu ft of air
(A) Saturated adiabatically (natural air drying)	1.0
(B) Heated to 140 F and saturated adiabatically (heated air drying)	9.8
(C) Saturated from hot corn at 140 F (dryeration)	104.3

The relative water-removal capacity of air used in three different drying situations is shown in Table 6. Ten times more water can be removed by passing 70 F air through corn already heated to 140 F than can be removed by first heating the same amount of air to 140 F, as in normal heated-air drying. The moisture removal during cooling is incident to the cooling process and proceeds at the same rate. After cooling, any drying or wetting of the corn proceeds at a much slower rate, as in natural-air drying.

Summary

When grain is cooled by aeration, its moisture content is reduced. When grain is warmed by aeration, moisture is added. The moisture change is incident to the temperature change and proceeds at the same rate.

The moisture losses are usually between 0.3 and 0.6 percent when dry grain is cooled by aeration according to recommended practices. The heat to evaporate the moisture comes from the grain and accounts for about half of the cooling. The air required is reduced proportionately.

Laboratory aeration tests showed that the moisture removed from wheat during cooling was within 20 to 30 percent

of the theoretical maximum. Aerating with air at relative humidities below those in moisture equilibrium with the grain resulted in greater moisture reduction and lower final grain temperatures. Cooling air with a relative humidity above equilibrium resulted in higher final grain temperatures and slightly less moisture removal. The moisture removed when grain was cooled from 80 to 50 F was less than the moisture added when the grain was warmed from 50 to 80 F.

The moisture-removal potential in aeration is exploited in the dryeration process when hot corn from a heated-air drier is cooled with aeration after a tempering period. In six tests, the moisture content of hot corn was reduced 2.1 percent when cooled from 142 F to about 50 F. The moisture removal accounted for about 60 percent of the cooling. This reduced the cooling air requirements to within practical limits for farm and elevator application. The hot corn was cooled in 10 to 14 hr with air flow rates of 0.5 cfm per bu.

References

1 Foster, George H. Dryeration—a corn drying process. AMS 532, U.S. Department of Agriculture, April 1964.

2 Kline, G. L. and Converse, H. H. Operating grain aeration systems in the hard winter wheat area. Marketing Research Report No. 480, U.S. Department of Agriculture, November 1961.