PAPER NO. 71-304

EFFECT OF TEMPERING AFTER DRYING ON THE COOLING OF SHELLED CORN

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For presentation at the 1971 Annual Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Washington State University
Pullman, Washington
June 27-30, 1971

SUMMARY:

Effect of tempering on cooling shelled corn was studied in the laboratory at three levels of cooling air flow rate. The results are presented and discussed along with a possible theoretical analysis based on diffusion theory.

American Society of Agricultural Engineers
St. Joseph, Michigan 49085

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INTRODUCTION

A recent advance in grain drying methods, called dryeration and consisting of three stages, was developed to reduce the brittleness and improve the quality of the dried grain. The three stages are (1) rapid drying with heated air to a moisture level 2 to 3 percentage points higher than the desired final moisture level, (2) tempering with no air flow for a prescribed length of time, and (3) cooling the grain slowly with low air flow rates to remove the final 2 to 3 percentage points of moisture by utilizing the heat in the grain.

A field study by Thompson and Foster (10)[1/] on dryeration of shelled corn showed that the amount of moisture removed during cooling increased as the tempering time increased. Under one heated air drying condition (187 F drying air temperature and 45 cfm/bu air flow rate), they found that the amount of moisture removed incident to cooling was higher after 8 hours of tempering than after 2-hour and 4-hour tempering periods. It was also higher than the amount of moisture removed after 12 hours of tempering. Thus, there appears to be an optimum length of time for tempering.

The purpose of this study was to determine the effect of tempering time on the cooling rate and on the moisture removal during the cooling of shelled corn.

TESTS, PROCEDURE, AND EQUIPMENT

A series of tests was conducted in the laboratory. The test procedure involved three stages. First, the corn was dried, then it was tempered before cooling, and finally it was cooled with air. A factorial

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1/ Numbers in parentheses refer to references cited.

experimental design was used involving five levels of tempering time (0, 1, 2, 4 hours, and complete), and three levels of cooling air flow rate (5, 20, and 75 cfm/bu). Sixty percent of the tests were replicated.

The equipment used in each test included a dryer, a cooler and a tempering cabinet. Also, a special test section was used to contain the grain.

Test Section

The test section was a cylinder made of fiberglass insulating meterial. Pieces of styrofoam were cut and fitted to the outside diameter of the column to provide more insulation. Bare and shielded copper-constantan thermocouples were installed on the center line at different distances from the bottom of the column, so that each location had one shielded thermocouple to indicate air temperature and a bare thermocouple to indicate an intermediate temperature considered to be halfway between that of the air and that of the grain. The shielding was accomplished by locating the thermojunction inside a plastic bead approximately 0.4 inches in diameter, with holes drilled to let the air through.

A transition section was constructed of 20-gauge galvanized sheet metal, well insulated and used to connect the dryer, or the cooler, to the test section. A 1/8" X 1/8" mesh screen was soldered to the top of the entrance section to support the grain. A thermocouple was installed at the center of the entrance 1 inch below the screen to measure the inlet temperature. Another thermocouple was located on the top surface of the grain at the center to measure the exhaust temperature.

A 24-point electronic recorder was used to record each temperature at 1/2-minute intervals.

Dryer

The drying was accomplished with a laboratory dryer that has a centrifugal fan and a set of electric heaters, controlled by a set of switches and a thermostat. The drying air flow rate was measured by a vane anemometer and adjusted by a damper and by changing the speed of the fan.

Tempering Cabinet

The corn was tempered in a cabinet constructed of two layers of 0.5-inch-thick plywood with 2 inches of styrofoam in between. The temperature was maintained by an electric heater controlled by a thermostat.

Cooler

The cooling air, maintained at near constant condition by an Aminco air conditioner, was forced with a rotary blower through an insulated galvanized sheet metal box and then through the grain in the test section. The cooling air flow rate was measured by a rotameter and controlled by a combination of a throttling valve and a relief valve.

Corn initially at about 23.5 percent moisture was dried to 17 ±0.2 percent, wet basis. The sample size was either 0.2 or 0.4 bushels. In all except for the complete tempering tests, the corn was dried in the 8-inch diameter test section using heated air at 165 ±5 F. Immediate cooling was considered as 0-hour-tempering. For the 1-, 2-, and 4-hour tempering, the test section with the grain was removed from the dryer, almost sealed with styrofoam lids at the top and the bottom, weighed, and put in the tempering cabinet. The temperature in the cabinet was adjusted and controlled at 145 ±2 F, the average temperature of the corn after drying was completed. After tempering, the test section was taken out of the cabinet, weighed, and the lids removed to start cooling.

The complete tempering was accomplished by drying the corn slowly with unheated air to 17 ±0.2 percent. After several hours, the corn was packed in almost-sealed metal cans, heated in an oven to 145 ±2 F, emptied in the test section, and cooling was started.

The temperatures of the air and grain were recorded throughout each test. The sample was weighed at 15-minute intervals.

TEST RESULTS AND ANALYSIS

Cooling

A temperature ratio for the grain defined as

$$TR_i = \frac{T_{gi} - T_a}{T_{goi} - T_a} \tag{1}$$

was used in the analysis, where TR_i is the temperature ratio at the ith location in the grain bed, T_{gi} is the grain temperature, T_{goi} is the original grain temperature at the ith location, and T_a is the cooling air temperature at the inlet, F. A dimensionless average temperature ratio for the whole bed of grain was calculated as follows:

$$TR_{av} = \frac{1}{2d}[(TR_0+TR_1)X_i + (TR_1+TR_2)X_2 +\text{---}+(TR_n+TR_e)X_n] \tag{2}$$

in which d is the total depth of the bed and TR_0 and TR_e are the temperature ratios at the entrance and the exit, respectively. X_i (i = 1, 2,--- n) is the distance between (i-1) and the ith location in the bed. Plots of TR_{av} versus time of cooling are shown in Fig. 1, 2, and 3 for the five levels of tempering and at the three levels of air flow rate.

For a comprehensive analysis that involves tempering time and air flow rate as independent factors, the data were arranged so that the time required to accomplish a certain percentage of cooling was used as the dependent variable. These data are given in Table 1. A detailed explanation of the technique used in the analysis, as well as the results of the analysis, are given by Sabbah (9).

As tempering time was increased, the rate of cooling increased, and the cooling time decreased at all levels of air flow rate. Similar results were obtained when the air flow rate was increased. The statistical analysis applied to the data indicated that the effect of both tempering and air flow rate on cooling time was highly significant (0.01 level).

TABLE 1. COOLING TIME REQUIRED AT THE DIFFERENT AIR FLOW RATES AND TEMPERING TIMES

Cooling air flow rate	Tempering time	Time required to reach cooling percentages of:				
		10	30	50	70	90
cfm/bu	hours	min.	min.	min.	min.	min.
5	0	9.00	28.00	54.60	96.75	165.50
	1	7.50	21.80	44.00	82.50	150.50
	2	6.50	19.90	37.00	72.50	142.00
	4	4.80	17.80	36.00	68.00	135.00
	C	3.75	15.00	30.75	64.00	126.75
20	0	1.40	11.00	21.25	37.75	66.00
	1	.80	5.35	12.50	26.75	51.75
	2	.70	4.70	11.75	24.75	50.25
	4	.40	4.15	11.50	23.50	47.00
	C	.25	3.35	10.50	21.25	45.50
75	0	1.20	5.35	9.40	14.50	22.50
	1	.50	3.00	7.00	12.50	22.00
	2	.50	3.00	7.00	12.00	20.50
	4	.30	2.50	6.00	11.50	21.00
	C	.50	2.50	6.75	12.00	20.50

The effect of tempering on cooling rate (and on cooling time) was more pronounced in the early stages of cooling and decreased as the cooling progressed. The effect of tempering on cooling time was more pronounced at low air flow rates and less effective at higher air flow rates. These relationships were statistically significant.

Moisture Removal

The effect of tempering on moisture removal incident to cooling was presented in terms of moisture ratio, MR_c, defined as follows:

$$MR_c = \frac{M-M_c}{M_f-M_c} \tag{3}$$

in which M is the average moisture content of the corn at any time during the cooling, M_f is the average moisture content of the corn after drying with heated air, and M_c is the final moisture content of the corn when no further moisture is removed incident to cooling. M_c is believed to be more appropriate for the drying incident to cooling than the equilibrium moisture content used in conventional drying calculations. M_c can be calculated as follows:

$$M_c = M_f - M_{max} \tag{4}$$

in which M_{max} is the maximum percentage of moisture that can be removed by the usable residual heat in the grain assuming that the exhaust air comes out at temperature and moisture equilibrium with the initial temperature and moisture content of the grain. It was calculated by applying a heat balance between the cooling air and the grain.

Fig. 4, 5, and 6 present plots of MR_c versus time of cooling for the three air flow rates. The data were statistically analyzed as given in Table 2.

TABLE 2. THE EFFECT OF AIR FLOW RATE AND TEMPERING TIME ON MOISTURE REMOVAL DURING COOLING OF CORN

Cooling air flow rate	Tempering time	The moisture ratio, MR_c 1/, at cooling percentages of:				
		10	30	50	70	90
cfm/bu	hours	MR_c	MR_c	MR_c	MR_c	MR_c
5	0	0.932	0.801	0.671	0.547	0.430
	1	.867	.765	.639	.515	.387
	2	.864	.750	.635	.514	.445
	4	.810	.630	.459	.302	.163
	C	.808	.582	.446	.264	.145
20	0	.968	.839	.745	.632	.531
	1	.959	.781	.665	.479	.370
	2	.935	.748	.623	.453	.315
	4	.923	.737	.615	.443	.295
	C	.915	.755	.611	.416	.316
75	0	.941	.862	.817	.775	.749
	1	.943	.870	.795	.732	.672
	2	.926	.840	.775	.727	.673
	4	.920	.848	.778	.709	.612
	C	.855	.746	.646	.578	.532

1/ See text, page 6, for definition of MR_c.

The amount of moisture removed incident to cooling decreased as the air flow rate increased at all levels of tempering. For example, following complete tempering and when cooling at air flow rates of 5 cfm/bu, about 90 percent of M_{max} was removed when 90 percent of the cooling was accomplished. At air flow rates of 20 cfm/bu, and complete tempering, about 68 percent of M_{max} was removed. At 75 cfm/bu, about 47 percent of M_{max} was removed. Thus, at low air flow rates, more of the residual heat in the corn was used in evaporating moisture.

As tempering time increased, the total amount and the rate of moisture removal incident to cooling increased at all levels of air flow rates. As a result, the time required to complete cooling of the grain decreased. For example, at 20 cfm/bu air flow rate, it took 66 minutes to accomplish 90 percent of the cooling and remove 0.47 M_{max} following no tempering. After complete tempering, and with the same air flow rate, it took 45.5 minutes to accomplish 90 percent cooling and to remove 0.68 M_{max}. The effect of tempering on cooling time was more pronounced at low air flow rates (5 and 20 cfm/bu), where large amounts of moisture were removed, than it was at high air flow rates (75 cfm/bu) where relatively small amounts of moisture were removed.

There is no explanation for the large increase in moisture removal indicated by increasing the tempering time from 2 to 4 hours in the cooling tests at the 5 cfm cooling air flow rate (Fig. 4). Apparently, the data from the 2-hour tempering tests are in error, since similar results did not occur in tests at 20 and 75 cfm/bu air flow rates (Fig. 5 and 6).

The statistical analysis showed that the effect of air flow rate and tempering on the moisture removal was significant at the 0.01 level. It showed also that the interaction between tempering and air flow rate was significant.

DISCUSSION

Drying grain with heated air establishes a moisture gradient as well as a temperature gradient in each kernel. Several workers have neglected the temperature gradient, and a uniform temperature has been assumed in both drying and cooling analyses. Even if the temperature gradient in the single kernel is not uniform after drying, it takes a very short time for the temperature to become uniform compared to the time required for the moisture gradient to disappear.

Ideally, tempering takes place in an airtight and well-insulated container so that no moisture escapes and no heat is conducted out of the grain. Under these conditions the change in the average temperature and moisture content of the grain due to tempering is negligible. The only change during tempering is in the moisture distribution in the kernels.

As cooling starts and cooling air passes through the hot grain, heat is transferred from the grain to the air in two forms, sensible (temperature reduction) and latent (moisture vaporization). The rate of sensible heat transfer and moisture removal are governed by internal and external resistances. The external resistances to both sensible heat transfer and moisture removal are dependent on the air velocity. The internal resistance to sensible heat transfer is very low and can be neglected. Thus, the rate of sensible heat transfer depends mainly on the air velocity. The internal resistance to moisture removal is dependent on the mass diffusivity which is a function of the temperature and moisture content of the grain. Thus, the rate of moisture removal and, accordingly, the rate of cooling attributed to moisture removal depends more on the temperature and moisture content of the grain and less on air velocity.

The amount of heat to be removed during the cooling due to sensible heat transfer and moisture removal is limited. Thus, as the air flow rate increases, the total amount of cooling attributed to sensible heat transfer increases, and the total amount of cooling attributed to moisture removal decreases. The air flow rate can reach a level where the amount of moisture removed becomes insignificant, and, therefore, all the cooling is due to sensible heat transfer. At this level of air flow rate, tempering has no effect on moisture removal or on cooling rate.

TEMPERING AND MOISTURE DIFFUSION THEORY

A rather detailed theoretical analysis was performed to provide a basis for predictions of the effect of tempering on moisture removal and cooling of grain. The following assumptions were made:

1. Internal moisture diffusion was the only significant process occurring during the tempering period. It was assumed to be isothermal and one-dimensional because the single kernel was assumed to be a sphere.

2. The moisture diffusing from the kernel surface to the interstitial space during the tempering process (no air flow) was neglected, and calculations showed that this actual amount of moisture was insignificant.

3. All the moisture in the kernel at the beginning of the tempering process was assumed to be concentrated at a point in the center of the kernel.

The time to complete the tempering process, t_{max}, was defined as the time when the moisture concentration at the surface reached its maximum. The equation derived was

$$t_{max} = R_k^2/6D \qquad (5)$$

where R_k equals the radius (feet) and D is the mass diffusivity of the kernel in ft^2/hr. Since the actual moisture distribution at the beginning of tempering cannot all be concentrated at one point, as stated in assumption 3, the actual time for complete tempering, t_c, can be more accurately estimated by

$$t_c = 0.8\ t_{max} \qquad (6)$$

This adjustment in t_c is based on the research data reported herein.

Mass diffusivity, D, is a function of grain temperature and moisture content. Data obtained by Chittenden and Hustrulid (5) and Baughman (2) were used to obtain the following expression for mass diffusivity as a function of M, moisture content, decimal, dry basis, and T_g, grain temperature, F.

$$D = 0.057\ M\ \ \exp\frac{-4812}{T + 460} \qquad (7)$$

Using this equation for corn initially at 19 percent moisture content and 140 F, t_c was found to be 9.7 hours. Under the same conditions in the field, Thompson and Foster (10) reported that in tempering trials of 2, 4, 6, 8, and 12 hours duration, the 8-hour period gave essentially complete tempering (no greater moisture removal during cooling was obtained with any of the other tempering periods).

A tempering index was formulated to predict the effect of partial tempering on the rate of moisture removal during drying. The above assumptions were used, and the tempering index is a function of the actual tempering time, t, the diffusivity, D, and the equivalent radius of the spherical kernel, R_k.

$$I = \frac{1.0}{(6tD/R_k^{\ 2} + 0.2)^{3/2}}\ \exp 3/2 \left(1.0 - \frac{1.0}{6tD/R_k^{\ 2} + 0.2} \right) \qquad (8)$$

In order to estimate the moisture removed during the cooling process, a drying equation is necessary which applies during the process of cooling grain that has been completely tempered. Development of such an equation was beyond the scope of this research. To predict the moisture content during cooling of partially tempered grain, a pseudo-initial moisture content, M_i, is used in place of the actual initial moisture content, and is calculated using the tempering index as follows:

$$M_i = I(M_f - M_o) + M_o \tag{9}$$

where M_o equals the original moisture content before heated air drying started and M_f equals the average moisture content of the grain after heated air drying is completed. Using data from this research, drying curves were plotted based on complete tempering and several levels of partial tempering, and the tempering index gave a reasonably accurate prediction of the actual drying curve for partially tempered grain. For more details, the reader is referred to Sabbah (9).

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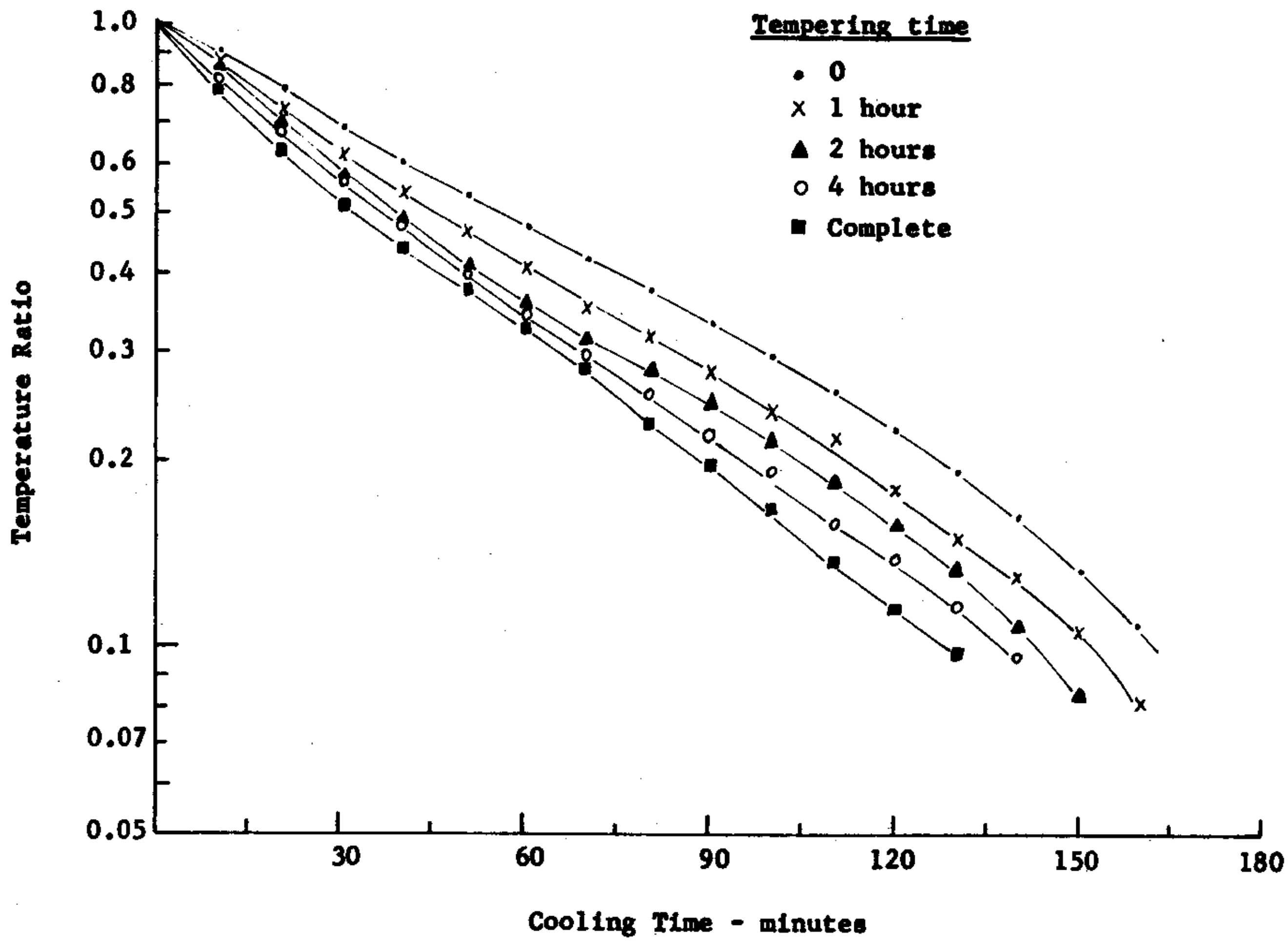

FIG. 1 Effect of tempering on the rate of cooling corn with 5 cfm/bu air flow rate

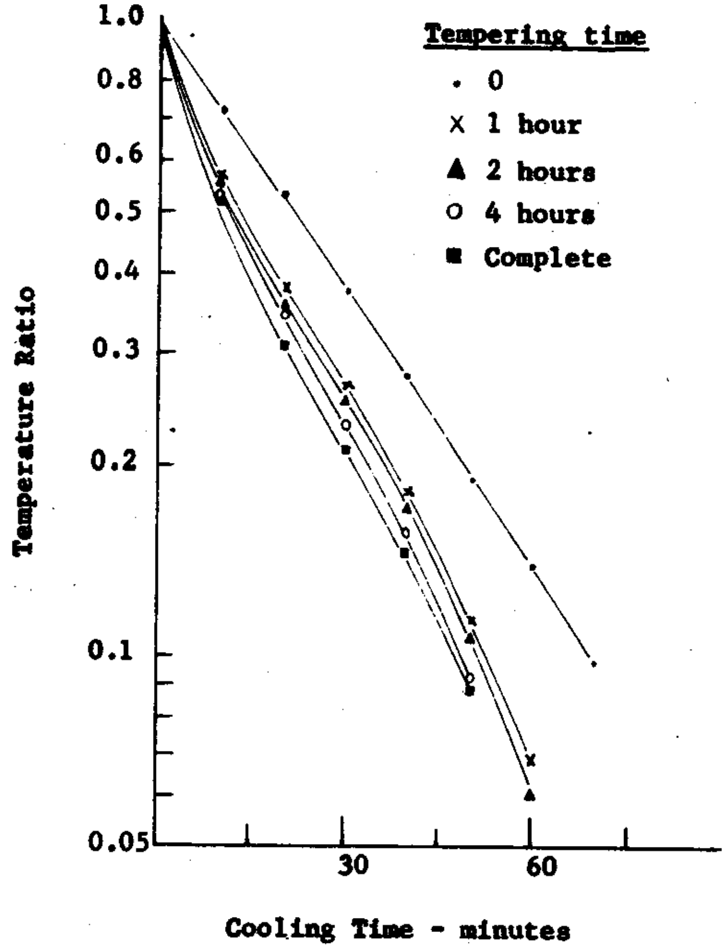

FIG. 2 Effect of tempering on the rate of cooling corn with 20 cfm/bu air flow rate

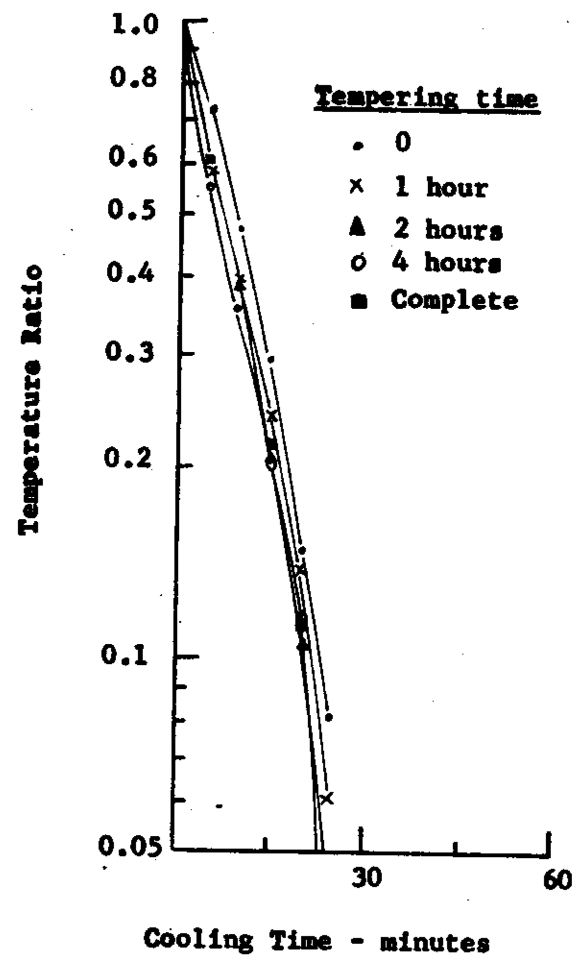

FIG. 3 Effect of tempering on the rate of cooling corn with 75 cfm/bu air flow rate

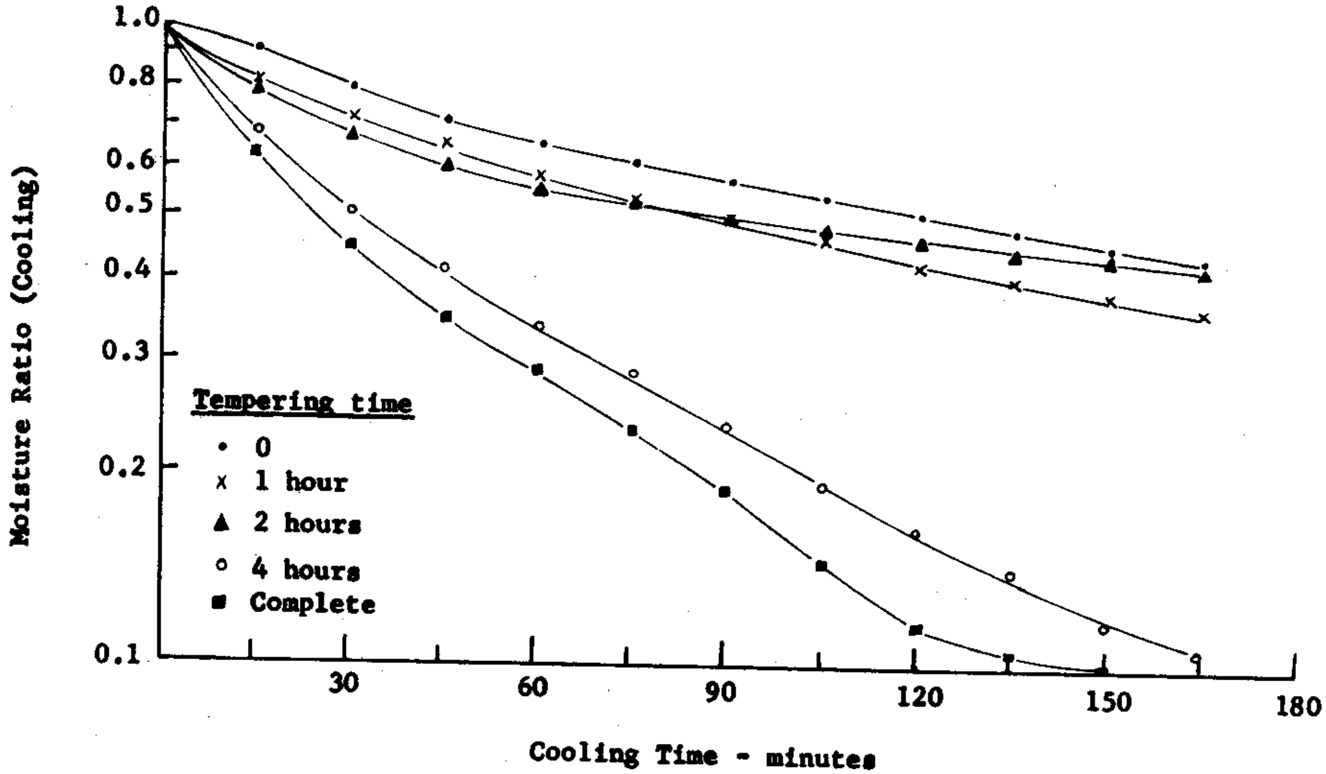

FIG. 4 Effect of tempering time on the amount of moisture removed during cooling of corn with 5 cfm/bu air flow rate

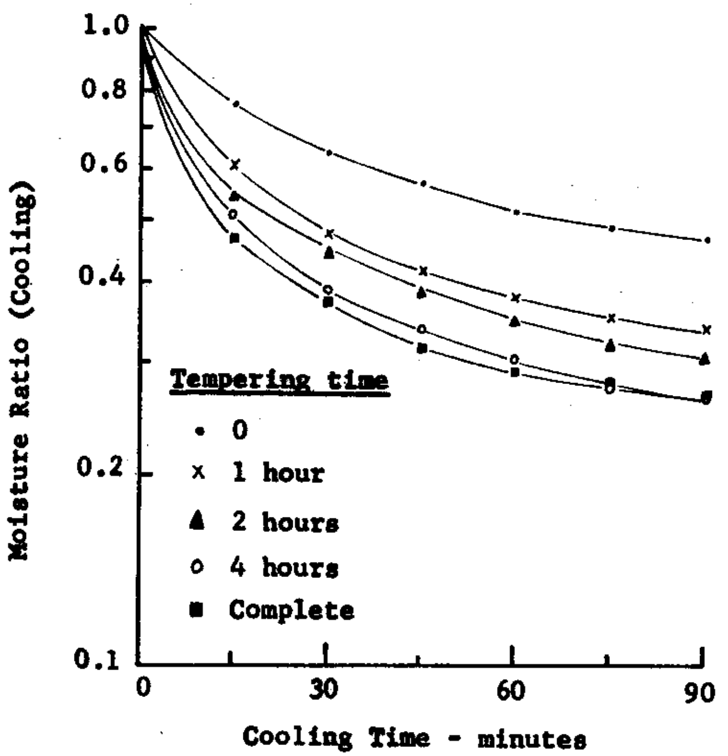

FIG. 5 Effect of tempering time on the amount of moisture removed during cooling of corn with 20 cfm/bu air flow rate

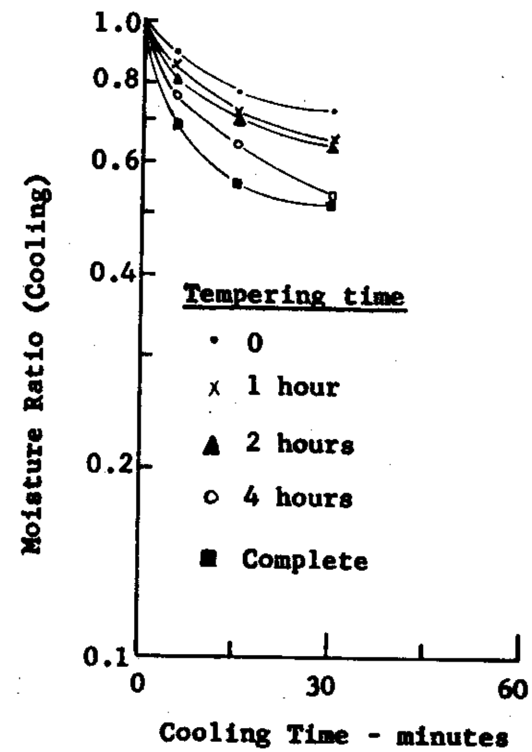

FIG. 6 Effect of tempering time on the amount of moisture removed during cooling of corn with 75 cfm/bu air flow rate