EFFECTS OF BASIC PARAMETERS IN DRYING GRAIN SORGHUM

OKLAHOMA STATE UNIVERSITY
INSTRUCTION RESEARCH EXTENSION
SCIENCE SERVING AGRICULTURE
1891
EXPERIMENT STATION

TECHNICAL BULLETIN
T-85

D. L. Day
and
G. L. Nelson

July 1960

CONTENTS

Effects of Basic Parameters in Drying GRAIN SORGHUM

By Donald L. Day and Gordon L. Nelson
Department of Agricultural Engineering, Oklahoma State University

The effectiveness of a forced air grain drying system is determined by several parameters such as initial grain moisture, temperature and humidity of drying air, air circulation rate, and other variables. The effect of these variables, or parameters, on the amount of drying accomplished needs to be known to design or manage a grain drying installation. A method for determining the drying effect for a specified set of conditions would be useful in design and in selecting operating conditions of a batch grain drying system.

The system considered in the present analysis included a batch or bed of grain sorghum of uniform depth and dried by forced circulation of heated or unheated air at a uniform rate.

The Background

Based on experimental research work at the Oklahoma Agricultural Experiment Station, a drying effect prediction equation has been developed by Nelson[1]. Variables in the prediction equation included average drying effect, bed depth, air circulation rate, elapsed time, initial grain moisture content,, and entering air temperature and relative humidity.

The form of the prediction equation obtained is:

$$E = [C_1(\Delta M \Delta T/T_e)^n]\,[1 - e^{-C_2\lambda/V\Phi}] \qquad \text{(equation 1)}$$

where:

The research reported herein was done under Oklahoma Agricultural Experiment Station Project 679.

E=Ave. drying effect by air, lb. of moisture removed from batch per lb. of dry air circulated, lb/lb.

ΔM=Difference, initial grain moisture minus equilibrium moisture corresponding to entering air state, lb. moisture per lb. dry grain.

ΔT=Difference, entering air dry bulb temperature minus "ideal" leaving air dry bulb temperature after constant wet bulb process to equilibrium humidity for grain at initial moisture content, °F.

T_e=Air dry bulb temperature entering grain, °F., absolute.

λ=Grain batch thickness or depth in direction of air flow, ft.

V=Air circulation rate through grain, cfm/ft^2.

Φ=Elapsed time since start of drying process, min.

e=base of natural system of logarithms.

In the present study, equation 1 was transformed to give the average moisture removed from the grain in percent dry basis by multiplying the right hand member by: $[V\Phi/\lambda]\,[\rho_a/\rho_g]100$
where:

ρ_a=density of air entering grain, lbs. dry air per ft^3 of mixture.

ρ_g=bulk densisty of the dry grain, lbs/ft^3.

This gave:

$$M_R = [C_1(\Delta M \Delta T/T_e)^n]\,[(1 - e^{-C_2\lambda/V\Phi})(V\Phi/\lambda)]\,[\rho_a/\rho_g]100 \qquad \text{(equation 2)}$$

where: M_R=average moisture removed from the grain, percent dry basis, during elapsed time Φ.

The dimensionless coefficients appearing in the equation were evaluated from experimental data obtained with a scaled down model and with field or full size drying installations. The experimentally determined values were: C_1=0.308, C_2=10,620 and n=0.774.

Analysis of Parameters

Equation 2 is not readily applicable to design or operating problems as it stands since it is inconvenient to evaluate, and supplementary information is required on equilibrium humidity and psychrometric properties of air.

In the present study, equation 2 was analyzed to obtain a rapid system for solving it numerically. This system can be used to evaluate the necessary operating conditions to produce a certain desired drying effect, or to evaluate the drying effect that will occur under given operating conditions, such as air circulation rate, air conditions, elapsed drying time, or batch depth. The predicted drying effect is an average drying effect in percent moisture reduction in the grain, dry weight basis. Usually the batch of grain in the dryer at the end of the drying operation will not have a uniform moisture content, but will have a moisture content lower than average where the air enters the grain, and higher than average where it leaves the grain. For uniform grain moisture content, the grain must be mixed after drying.

The numerical solution was based upon an analysis of each of the bracketed terms on the right hand side of equation 2. The following nomenclature was used for the analysis:

$K_1 = C_3(\Delta M \Delta T / T_e)^n$ = Drying potential index, where $C_3 = 308$.

$K_2 = \lambda / V\Phi$ = Circulation index

$K_3 = (1 - e^{-C_2 \lambda / V\Phi})(V\Phi/\lambda)$ = Circulation function

$K_4 = \rho_a / \rho_g$ = Density ratio.

Drying Potential Index, K_1—The analysis of the effects of outdoor air condition, air heating, and grain moisture on the value of the drying potential index K_1 is presented in Table I. The grain equilibrium moisture content corresponding to entering air state for use in computing ΔM was arrived at by using the equation developed by Henderson[2]:

$$1 - RH = e^{-A' T M_e^{\alpha}} \qquad \text{(equation 3)}$$

where:

RH=relative humidity expressed as a decimal.

TABLE 1
DRYING POTENTIAL INDEX — K_1

TEMP. OF AIR ENTERING GRAIN °F.	OUT-DOOR AIR TEMP. °F.	OUTDOOR AIR RELATIVE HUMIDITY, %														
		40					50					60				
		INITIAL GRAIN MOISTURE CONTENT, % DAMP BASIS														
		18	17	16	15	14	18	17	16	15	14	18	17	16	15	14
40	40	1.80	1.51	1.03	0.927	0.641	1.32	1.11	0.741	0.427	0.270	0.872	0.628	0.410	0.209	0.0603
60	40	4.34	3.91	3.39	2.86	2.37	3.58	3.33	2.91	2.48	1.99	3.38	3.00	2.55	2.11	1.60
	60	2.56	2.16	1.74	1.36	0.967	1.91	1.51	1.02	0.813	0.470	1.11	0.970	0.659	0.345	0.0934
80	40	7.27	6.71	6.01	5.36	4.56	6.33	6.00	5.60	4.92	4.22	6.42	5.86	5.19	4.56	3.82
	60	5.48	4.90	4.31	3.76	3.03	4.68	4.10	3.54	3.02	2.34	4.31	3.70	3.23	2.46	2.06
	80	3.26	2.74	2.28	1.56	1.25	2.31	2.03	1.57	1.11	0.656	1.54	1.17	1.05	0.542	0.224
100	40	10.2	9.36	8.50	7.70	6.75	9.79	9.23	8.21	7.39	6.42	9.31	8.55	7.78	7.05	5.97
	60	8.32	7.55	6.78	5.93	5.08	8.07	7.27	6.56	5.70	4.84	7.39	6.65	5.98	5.11	4.31
	80	6.41	5.64	5.05	4.31	3.39	5.08	4.87	4.13	3.39	2.71	4.84	4.25	3.63	2.99	2.31
	100	3.91	3.26	2.74	2.13	1.54	2.83	2.34	1.91	1.36	0.893	1.82	1.42	1.05	0.641	0.391
120	40	13.1	12.2	11.2	10.2	9.10	12.9	12.0	10.8	10.0	8.94	12.3	11.4	10.5	9.57	8.49
	60	11.5	10.7	9.70	8.72	7.70	11.1	10.2	9.12	8.29	7.27	10.66	9.79	9.49	8.01	6.96
	80	9.86	8.99	8.01	7.08	6.10	8.75	7.95	7.15	6.22	5.33	8.19	7.39	6.65	5.79	4.93
	100	7.39	6.33	5.76	4.90	4.10	6.28	5.21	5.00	4.16	3.39	5.33	4.65	4.00	3.30	2.59
140	40	16.0	15.0	13.9	12.8	11.6	15.8	14.8	13.5	12.3	11.2	15.5	14.4	13.2	12.1	10.9
	60	14.7	13.7	12.6	11.5	10.4	14.2	13.2	12.0	10.8	9.8	13.6	12.6	11.6	10.5	9.4
	80	12.8	11.9	11.0	9.86	8.75	12.2	11.3	10.4	9.24	8.13	11.5	10.5	9.58	8.35	7.39
	100	10.6	9.7	8.81	7.82	6.56	9.49	8.69	7.82	6.84	5.76	8.69	7.33	7.08	6.16	5.17
160	40	18.9	17.6	16.4	15.1	13.7	18.2	16.9	15.8	14.5	13.3	18.1	16.8	15.7	13.5	13.1
	60	17.6	16.5	15.3	14.0	12.8	17.0	15.9	14.8	13.6	12.3	16.5	15.4	14.3	13.1	11.9
	80	16.0	14.8	13.8	12.6	11.4	15.1	14.2	13.1	11.8	10.7	14.8	13.8	13.1	11.5	10.4
	100	14.1	13.1	11.6	10.8	9.64	12.9	12.0	11.0	9.86	8.62	12.2	11.1	10.3	9.15	7.92
180	40	21.2	19.9	18.5	17.1	15.8	20.7	19.5	18.5	16.9	15.5	20.5	19.2	18.0	16.6	15.3
	60	20.2	18.9	17.7	16.3	14.9	19.9	18.6	17.3	16.0	14.7	19.5	18.2	16.9	15.6	14.3
	80	18.8	17.6	16.4	15.0	13.6	18.2	17.0	15.8	14.5	13.1	17.6	16.4	15.3	13.9	12.5
	100	17.1	15.7	14.7	13.3	12.1	17.0	15.3	14.1	12.9	11.4	15.4	14.2	13.2	11.8	10.6

TABLE 1—(Continued)
DRYING POTENTIAL INDEX — K_1

TEMP. OF AIR ENTERING GRAIN °F.	OUT-DOOR AIR TEMP. °F.	OUTDOOR AIR RELATIVE HUMIDITY, % 70					80				
		INITIAL GRAIN MOISTURE CONTENT, % DAMP BASIS									
		18	17	16	15	14	18	17	16	15	14
40	40	0.541	0.323	0.156	0.028		0.185	0.0645			
60	40	3.10	2.71	2.23	1.84	1.37	2.75	2.39	1.94	1.51	1.08
	60	0.700	0.593	0.295	0.0574		0.239	0.0741			
80	40	5.94	5.37	4.80	4.10	3.40	4.95	4.39	3.88	3.23	2.59
	60	3.76	3.23	2.68	2.25	1.63	3.33	2.83	2.34	1.88	
	80	1.05	0.678	0.317	0.0862		0.283	0.101			
100	40	9.00	8.24	7.47	6.71	5.97	8.86	8.07	7.30	6.54	5.26
	60	7.08	6.28	5.45	4.80	4.03	6.47	5.79	4.96	4.31	3.54
	80	4.19	3.63	2.96	2.31	1.72	3.48	2.96	2.43	1.85	0.385
	100	1.11	0.770	0.493	0.185		0.339	0.190	0.0437		
120	40	12.1	11.2	10.1	9.25	8.24	11.5	10.6	9.79	8.72	7.73
	60	9.95	9.09	8.32	7.42	6.38	9.79	8.87	8.10	7.08	6.25
	80	7.58	6.84	6.10	5.21	4.44	6.99	6.25	5.58	4.77	3.94
	100	4.62	4.00	3.42	2.86	2.28	3.82	3.30	2.74	2.03	1.45
140	40	15.0	13.9	12.8	11.9	10.5	14.7	13.7	12.6	11.4	10.3
	60	13.2	12.3	11.2	10.3	9.02	12.9	11.9	11.0	9.86	9.46
	80	10.7	9.70	8.78	7.85	6.84	10.3	8.75	8.50	7.48	6.53
	100	7.64	6.87	5.88	5.11	4.19	7.24	6.41	5.67	4.84	3.94
160	40	17.9	16.8	15.6	13.4	13.1	17.6	16.3	15.3	14.0	12.8
	60	16.3	15.1	14.0	12.8	10.1	16.0	14.8	13.7	12.4	11.1
	80	14.2	13.1	12.0	10.9	9.61	13.7	12.6	11.7	10.5	9.24
	100	11.4	10.5	9.55	8.47	7.30	10.9	9.98	9.09	8.01	6.84
180	40	20.4	19.2	17.7	16.6	15.2	20.2	19.0	17.9	16.3	14.9
	60	19.4	18.1	16.8	15.4	14.2	19.1	17.6	16.4	15.1	13.8
	80	17.4	17.1	15.1	13.9	12.7	16.9	15.6	14.4	13.2	12.1
	100	14.8	13.7	12.6	11.2	10.1	14.1	12.9	12.0	10.6	9.42

T=absolute temperature, °F.

M_e=The equilibrium moisture content, % dry basis.

For grain sorghum[2]:

$A' = 3.4 \times 10^{-6}$

$\alpha = 2.31$

Hall[3] questioned the validity of equation 3 when used for predicting values at other than 77°F., the temperature at which the equilibrium moisture content was measured for evaluation of the constants A′ and α in equation 3. However, equation 3 seemed to hold well for grain sorghum[3] over a range of temperatures, so it was used to calculate equilibrium moisture contents. Equilibrium moisture curves were plotted for grain sorghum at temperatures ranging from 40°F to 180°F, as shown in Figure 1. Psychrometric charts were used to determine the relative humidity of the air entering the grain for heated air.

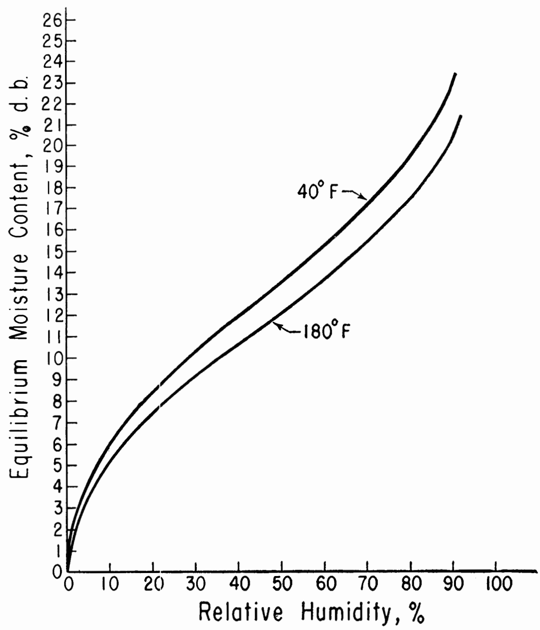

Figure 1: Equilibrium Moisture Content for Grain Sorghum.

To determine the ideal leaving air temperature, grain sorghum equilibrium moisture content curves were superimposed upon psychrometric charts. "Ideal" leaving air dry-bulb temperature was found on the psychrometric charts by following a constant wet-bulb process line from entering air conditions to the intersection of the wet-bulb line with the equilibrium curve corresponding to the initial moisture content of the damp grain. The "ideal" leaving temperature was the dry bulb temperature at this point. ΔT was then computed by subtracting this "ideal" leaving temperature from the entering air dry-bulb temperature.

When reading K_1 values from Table I, the average outdoor air conditions which prevail during the drying period should be used. The

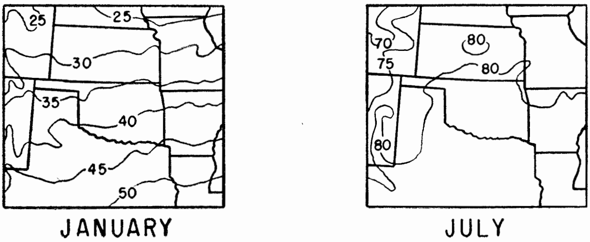

Figure 2: Average Temperature, °F, 1899-1938.

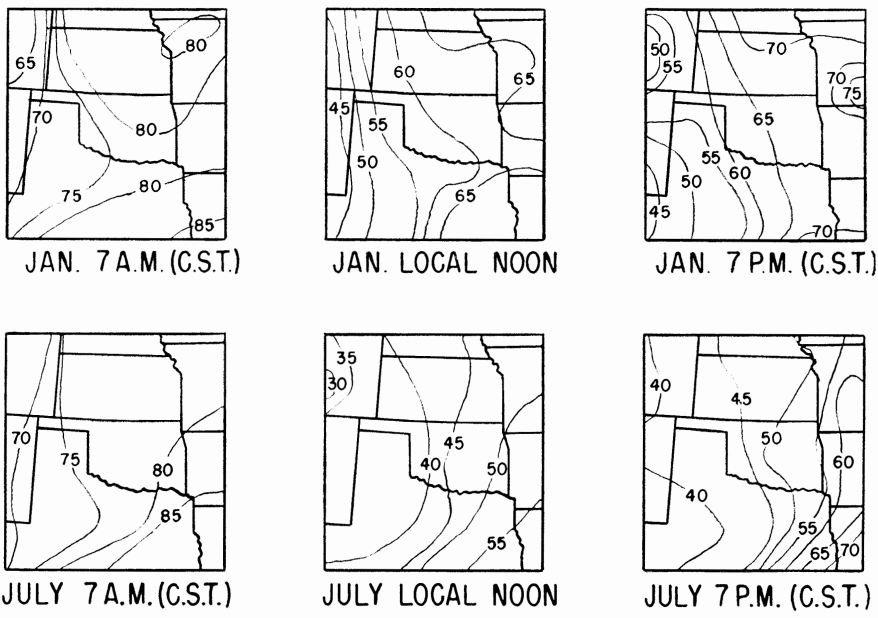

Figure 3: Average Relative Humidity, %, 1899-1938.

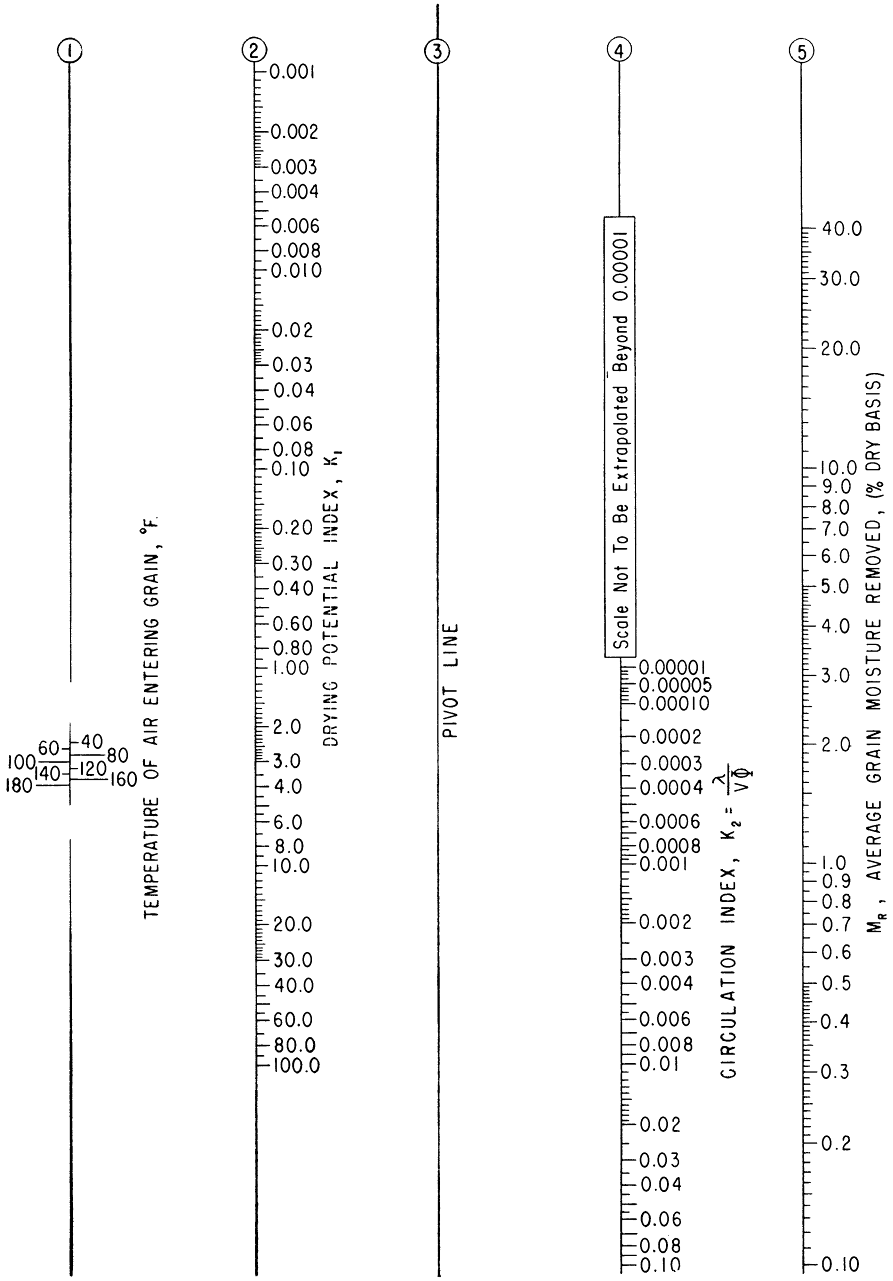

Figure 4: Nomograph of Basic Parameters.

outdoor air average temperature and relative humidity should be evaluated from the most accurate information available. For planning purposes [4], Figures 2 and 3 may be helpful for estimating outdoor air average conditions in Oklahoma.

Values of K_1 are plotted on line 2 of Figure 4.

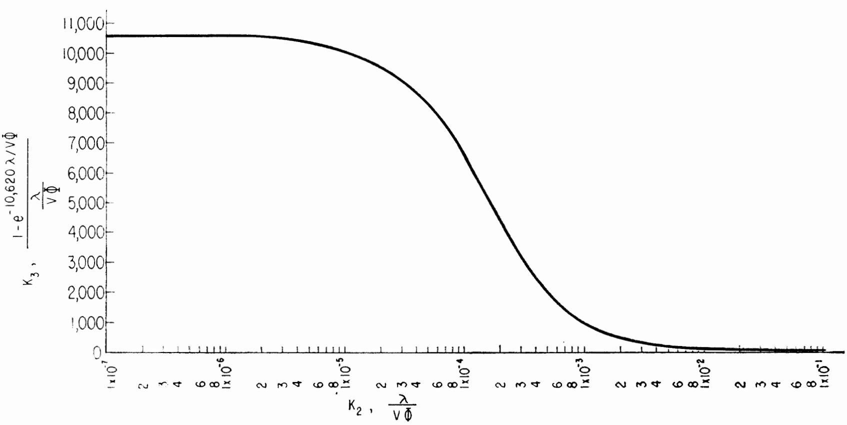

Figure 5: Circulation Function, K_3, vs. Circulation Index, K_2.

Circulation Index K_2 and Circulation Function K_3: Figure 5 is a graph of the circulation function, K_3, for a range of values of the circulation index, K_2, from 1 x 10^{-7} to 1 x 10^{-1}. The maximum attainable value of K_3 is 10,620, which occurs at K_2=0. This is not attainable in a practical situation. Line 4 of Figure 4 has a range of values of $\lambda/V\Phi$ from 0.10 to a minimum of 0.00001, which was considered to be the minimum practical value, and gives a drying effect close to the maximum attainable effect.

Density Ratio K_4: ρ_a was evaluated for an average moisture content in the air entering the grain. A moisture content of 0.005 pounds of moisture per pound of dry air was selected as being appropriate for the usual range of ambient air conditions. Small changes from this selected value produced negligible changes in the final solution of equation 2. ρ_g=35.53 lbs. dry grain per ft^3 was calculated using the density of grain sorghum=44.8 lbs. per ft^3 at an assumed moisture content of approximately 14%, wet basis[5]. The temperatures of air entering the grain corresponding to the ratio ρ_a/ρ_g for these temperatures are plotted on line 1 of Figure 4.

It should be noted that the solution to equation 2 gives moisture removed on a **percent dry weight basis.** Figure 6 is included for convenience when converting grain moisture content from damp weight to dry weight basis and vice versa, since grain moisture is often given on a damp weight basis.

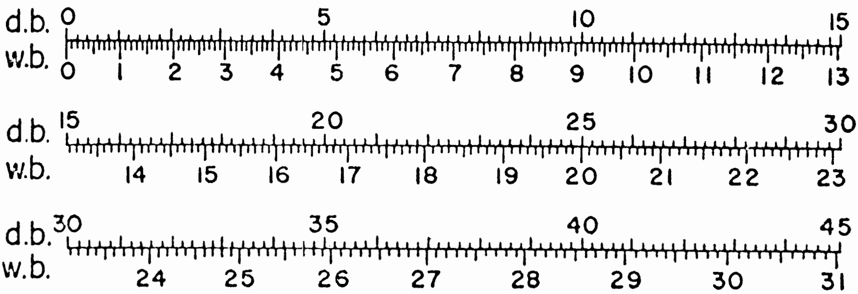

Figure 6: Equivalent Moisture Percentages; d.b=% Dry Basis, w.b=% Damp (Wet) Basis.

Instructions and Sample Problems for Using Tables and Charts

Problem Type A. Computing required length of time, or grain depth, or circulation rate to remove a definite percent of grain moisture.

Example Problem (Refer to Figure 7).

Known conditions:

Initial grain moisture=15% damp basis

Outdoor air temperature=60°F.

Outdoor relative humidity=70%.

Temperature of air entering grain=80°F.

Depth of grain, λ=8 ft.

Air circulation rate, V=30 Cfm/ft².

Required—the time, Φ, required to dry grain to 12% moisture wet basis.

From Table I, K_1=2.25. Locate K_1 on line 2 of Figure 7.

Locate temperature of air entering grain, 80°F, on line 1 of Figure 7.

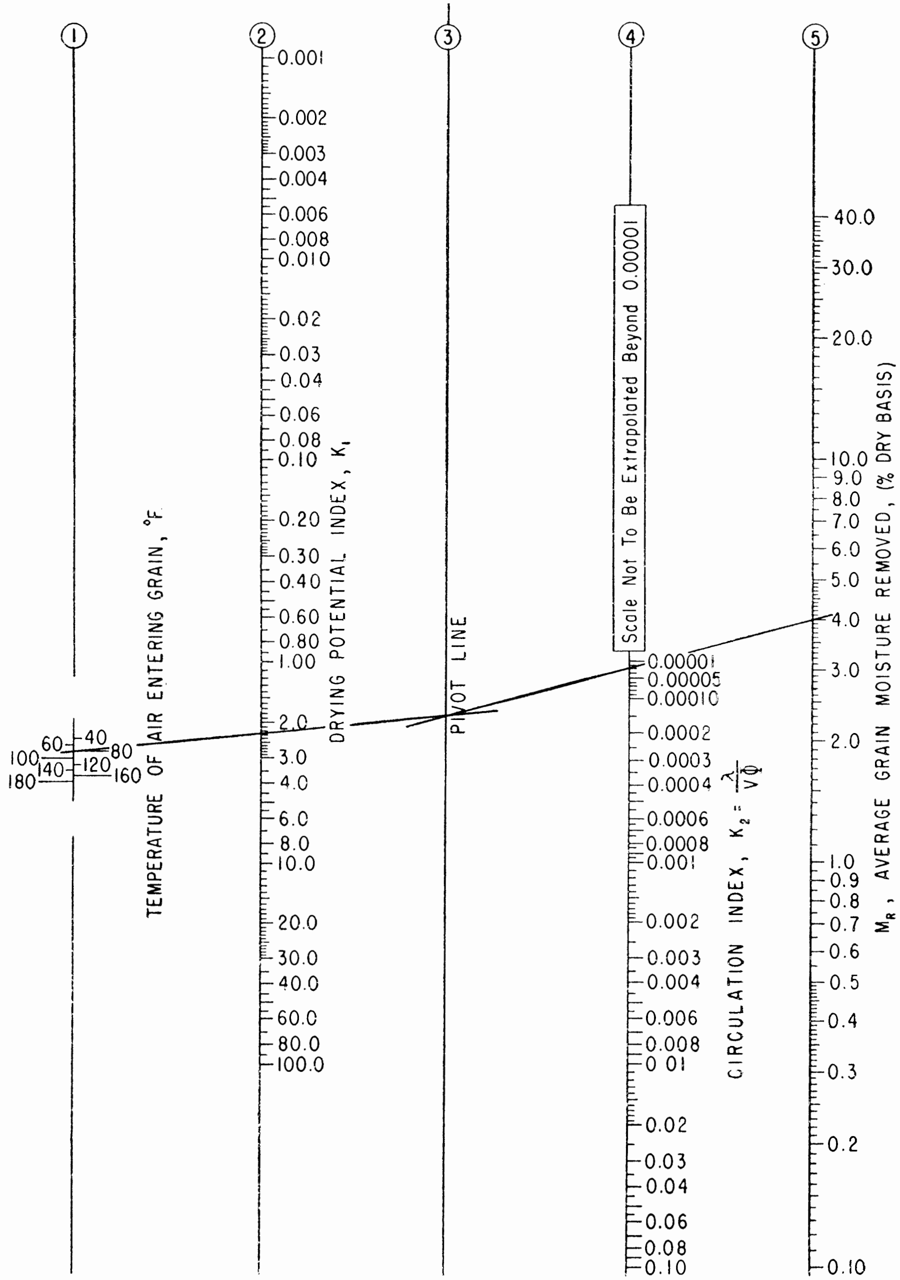

Figure 7: Solution to Example Problem Type A.

Draw a straight line through these points on line 1 and line 2 and extend to line 3, the pivot line.

From Figure 6, read:

Initial grain moisture=17.6% dry basis

Final grain moisture=13.6% dry basis

M_R=17.6−13.6=4.0% dry basis.

Locate 4.0% on line 5 of Figure 7 and connect this point with point previously located on line 3.

Read K_2=0.00003 at point of intersection on line 4.

Solve for $\Phi=\lambda/VK_2$

$\Phi=8/(30)(0.00003)=8{,}900$ minutes

This is approximately 6¼ days.

The same procedure is followed if grain depth, λ, or circulation rate, V, is to be determined, when time, Φ, and either V or λ are known, by determining K_2 from Figure 7 and solving for the unknown quantity in the expression $K_2=\lambda/V\Phi$.

Problem Type B. Computing the percent grain moisture removed if the drier is operated a definite length of time with a specified grain depth and air circulation rate.

Example Problem (Refer to Figure 8).

Known conditions:

Initial grain moisture=18% damp basis.

Outdoor air temperature=40°F.

Outdoor relative humidity=70%.

Temperature of air entering grain=140°F.

Depth of grain, λ=1 ft.

Air circulation rate, V=20 cfm/ft^2.

Time drier is to be operated, Φ=120 minutes.

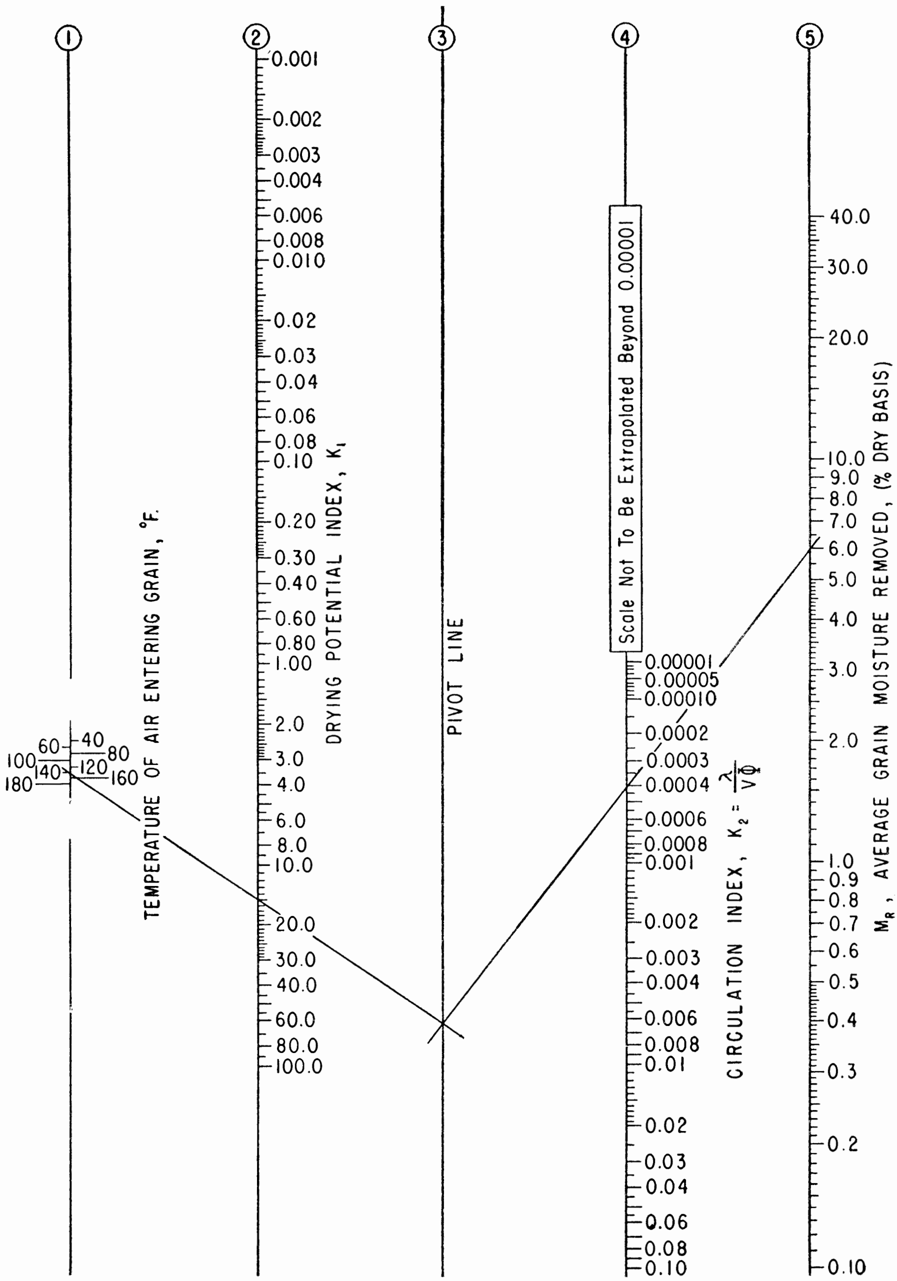

Figure 8: Solution to Example Problem Type B.

Required—To find moisture removed, M_R, and final moisture content, % damp basis.

From Table I, K_1=15.0

Locate K_1 on line 2 of Figure 8.

Locate temperature of air entering grain, 140°F., on line 1 of Figure 8.

Draw a straight line through the points on line 1 and on line 2 and extend the line until it intersects line 3, the pivot line.

Compute $K_2=\lambda/V\Phi=1/(20)(120)=0.000417$ and locate on line 4 of Figure 8.

Draw a straight line from this point to the point previously located on the pivot line and extend until it intersects line 5.

Read moisture removed, M_R=6.0% dry basis

Use Figure 6 to find initial moisture, % dry basis=21.9%.

Final moisture=21.9%—6.0=15.9% dry basis

From Figure 6, final moisture=13.7% damp basis.

Problem Type C—Determining required temperature of air entering the grain for removing a definite percent of grain moisture when drying time, air circulation rate, and bed depth are known.

Example Problem (Refer to Figure 9)

Known conditions:

Initial grain moisture=14% damp basis.

Final desired grain moisture=11% damp basis

Outdoor air temperature=80°F.

Outdoor air relative humidity=60%

Depth of grain, λ=1 ft.

Air circulation rate, V=16 cfm/ft^2.

Drying time, Φ=125 minutes.

Required—the temperature of air entering grain to dry the batch from 14% to 11% damp basis in 125 minutes.

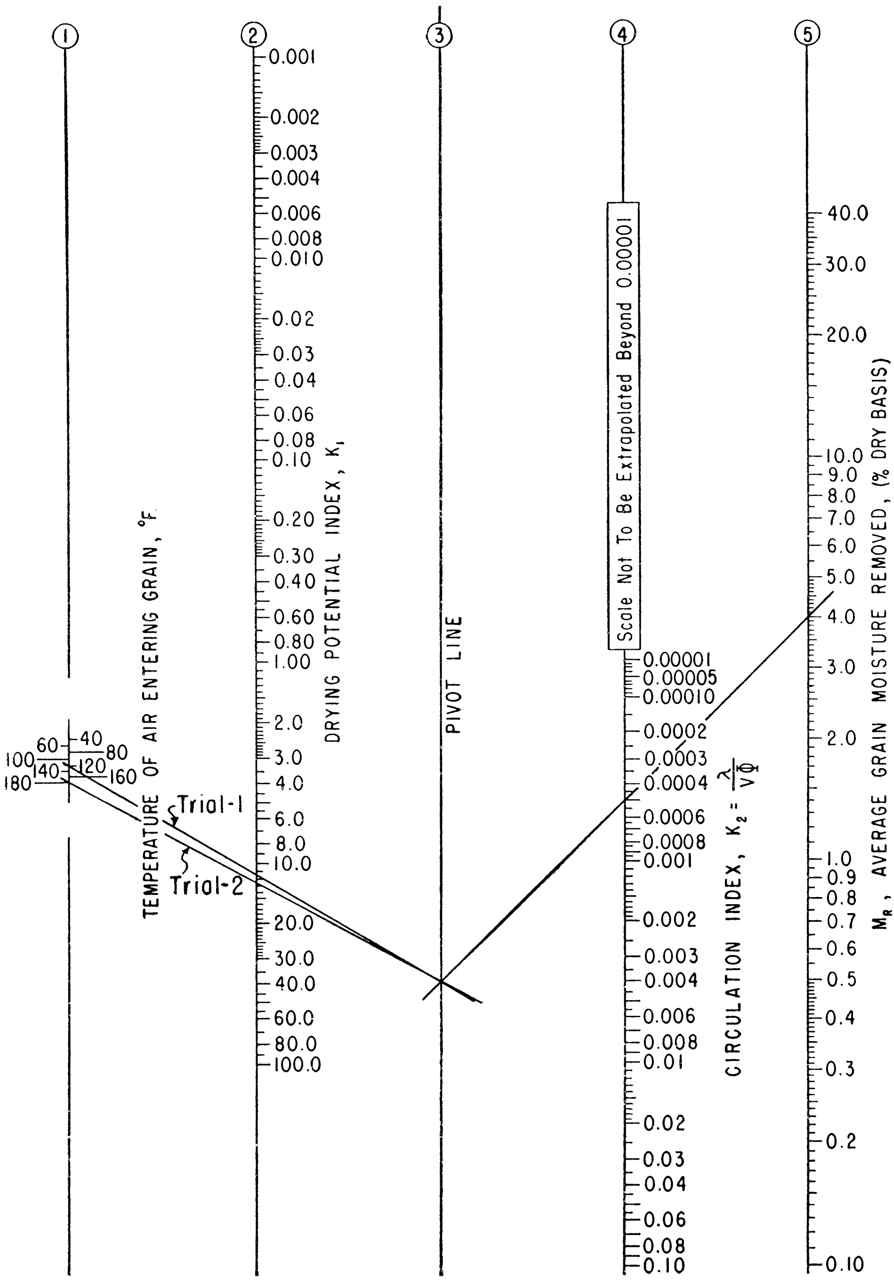

Figure 9: Solution to Example Problem Type C.

By using Figure 6, convert initial and final grain moistures to % damp basis, 16.3% and 12.3% respectively. Moisture to be removed, M_R=16.3—12.3=4% dry basis. Locate M_R on line 5 of Figure 9.

Compute $K_2=\lambda/V\Phi=1/(16)(125)=0.0005$. Locate K_2 on line 4.

Draw a straight line through M_R and K_2 and extend the line until it intersects line 3, the pivot line.

Connect the point of intersection on the pivot line with a trial entering air temperature near the midpoint of the scale on line 1, 120°F, and read a trial value of K_1=11.5 on line 2. From Table I, K_1=11.5 corresponds to an entering air temperature between 160 and 180°F. Check a trial value of 180°F. by drawing a line from the point previously established on the pivot line to 180°F. on line 1 of Figure 9. Read a new trial K_1=12.5. This checks with the K_1 value in Table I corresponding to 180°F. entering air temperature, so the solution is complete. Required temperature of air entering grain is 180°F. If the first trial value of K_1 was higher than any listed in Table I corresponding to the given conditions, a new value of $\lambda/V\Phi$ must be selected because the drying cannot be accomplished in the original desired time, unless either or both the air circulation rate and grain depth are adjusted.

Summary

A prediction equation has been developed whereby the drying effect of air circulated through a bed of grain can be calculated. The drying system considered is one that includes a batch or bed of grain of uniform depth and dried by forced circulation of heated or unheated air at a uniform rate. A system of tables and charts from which the solution of the prediction equation may be conveniently obtained is presented. Alignment charts are used for the final solution of the equation. The analysis can be used to solve three basic types of problems in design or operation of grain drying system. These include: A—Computing required circulation index; B—Computing average grain moisture removed; and C—Computing heated air temperature required.

Literature Cited

1. Nelson, G. L. "A New Analysis of Batch Grain Dryer Performance", Paper No. 59-415 presented at the annual meeting of the American Society of Agricultural Engineers, Ithaca, New York. June 21-24, 1959.

2. Henderson, S. M. "A Basic Concept of Equilibrium Moisture". *Agricultural Engineering Journal*, Vol. 33, 1952. pp. 29-32.

3. Hall, C. W. *Drying Farm Crops*. Agricultural Consulting Associates, Inc., Reynoldsburg, Ohio. 1957. p. 20.

4. *Climate and Man*. Yearbook of Agriculture 1941. United States Department of Agriculture, Washington, D.C., United States Government Printing Office. pp. 701-747.

5. *Agricultural Engineers Yearbook*. The American Society of Agricultural Engineers, 1959. p. 117.

ACKNOWLEDGMENT

Assistance in developing the nomograph, Figure 4, was contributed by James E. Garton, Associate Professor, Agricultural Engineering Department, Oklahoma State University.

7-60/2½M