SHELLED CORN CO_2 EVOLUTION AND STORAGE TIME FOR 0.5% DRY MATTER LOSS

C. J. Bern, J. L. Steele, R. V. Morey

ABSTRACT. *Following harvest, corn raised for grain is subject to infection and deterioration due to storage fungi. Laboratory storage studies done on yellow dent corn in the 1960s established dry matter loss, as estimated by CO_2 evolution during storage, to be a usable indicator of corn deterioration during storage. As a result of these studies, equations were developed to predict CO_2 evolution of stored corn as a function of moisture content, temperature, and mechanical damage level. Later research has added information on genetic hybrid resistance to fungal growth and fungicide effects. This article assembles the original equations derived from 1960s studies, plus relevant results from later research, into a comprehensive set of equations to predict CO_2 evolution and dry matter loss for corn stored at 15 to 35% moisture content (wet basis) and temperatures from 0 to 49° C. Effects of mechanical damage, genetic resistance to fungi, and fungicides are considered. A table of predicted shelled corn storage times for 0.5% dry matter loss and a table of multipliers for other dry matter loss levels are presented.*

Keywords. *Corn storage, Carbon dioxide, Deterioration, Respiration.*

After yellow dent corn (*zea maize L.*) raised for grain reaches physiological maturity, kernel moisture decreases until harvest, which usually takes place when kernel moisture is between 15 and 30% (all moistures are % wet basis). Following harvest, corn kernels are subject to infection by and deterioration due to storage fungi. The rate of deterioration during storage depends on storage time, kernel moisture, kernel temperature, kernel mechanical damage level, genetic susceptibility to storage fungi infection, and other factors. The ability to predict deterioration rate, as well as the storage time remaining before a certain deterioration level is attained, is very important in the design and management of corn storage and drying systems. For example, unacceptable fungal activity can occur in wet corn held too long in bins prior to drying. During natural air–drying, bins are often filled with wet corn in one or two days, and corn near the top of the bin may remain at high moistures for weeks or months before being dried.

Laboratory storage studies done in the 1960s established dry matter loss, as estimated by CO_2 evolution during storage, as a suitable indicator of corn deterioration (Saul and Steele, 1966; Steele, 1967; Steele et al., 1969). These studies modeled the total respiration of a corn mass under aerobic conditions as the oxidation of glucose:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 2835\text{kJ/gram mole} \quad (1)$$

With this assumption, CO_2 evolved is directly proportional to dry matter loss and 14.66 g CO_2 per kg original dry matter corresponds to a 1% loss of dry matter. Several later laboratory studies of corn deterioration also measured evolved CO_2 as an indicator of deterioration (Saul 1970; Friday et al., 1989; Al–Yahya et al., 1993; Wilcke et al., 1993; Ng et al., 1998; Gupta et al., 1999).

Saul and Steele (1966) suggested an allowable dry matter loss (DML) of 0.5% for field–shelled corn having 26 to 41% visible kernel mechanical damage by weight. They observed that at 0.5% DML, the corn would have no more than 5% by weight of kernels with visible mold damage and would, therefore, not be graded lower than USDA No. 2 due to the total damaged kernels (DKT) criterion. They further concluded that allowable DML can be assumed negatively proportional to mechanical damage, in the 2 to 30% mechanical damage range.

Ng et al. (1998), reporting on studies of combine–harvested 22 and 25% moisture corn, further defined this relationship and found allowable DMLs to range from 0.25% (for D = 50%) to 1.2% (for D = 0%). For combine–shelled corn with D = 25 to 35%, they found the allowable DML to be 0.35%. Gupta et al. (1999) showed allowable DML to be moisture dependent, with 18 and 22% moisture corn having allowable DMLs of 0.5 and 0.2%, respectively, for combine–harvested corn. Storage time tables and graphs for corn are usually based on an allowable DML of 0.5% (MWPS, 1987; Jones and Grisso, 1995; Brooker et al., 1992).

PURPOSE

The extensive work on corn storage and deterioration described in Steele (1967), Steele et al. (1969), and

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Thompson (1972) provides a basis for predicting CO_2 evolution from stored corn and predicting time for some level of DML. Steele et al. (1969) includes a graph of storage time for 0.5% DML versus storage temperature for various corn moisture levels. However, Thompson (1972) includes results of later work not reflected in Steele et al. (1969). Furthermore, these sources are not user–friendly, and research since 1972 has added valuable information. Numerous tables and graphs for predicting allowable corn storage time have been published, often citing Steele's research results or Thompson (1972) as their source, but not explaining how the tables and graphs were derived (Brooker et al., 1992; Jones and Grisso, 1995; Loewer et al., 1994; MWPS, 1983, 1987; Hunt, 1995). Consequently, their reliability can be questioned. The purpose of this article is to assemble the original results from Steele (1967), plus relevant later analysis and research results, into a complete set of equations to predict stored corn CO_2 evolution and corn storage time for desired DML levels.

Prediction of Corn Dry Matter Decomposition

Carbon dioxide production for corn under reference conditions (T = 15.6°C, M = 25%, D = 30%) can be predicted by equation 2, derived using data from Steele (1967) (Thompson, 1972):

$$Y = 1.3(e^{0.006t_s} - 1) + 0.015t_s \tag{2}$$

t_s is the time in hours under reference conditions. For 0.5% DML (Y = 7.33 gCO_2/kg DM in eq. 2), t_s is 230 h or 9.583 days.

Equation 3 was derived to calculate corresponding times at non–reference conditions. (Steele, 1967):

$$t_n = t_s M_M M_T M_D \tag{3}$$

M_M, M_T, and M_D are multipliers used to account for different moistures, temperatures, and visible mechanical damage levels (Steele, 1967).

Other research (Al–Yahya et al., 1993; Friday et al., 1989; Stroshine and Yang, 1990; Wilcke et al., 1993) has added information to allow use of additional multipliers for predicting effects of genetic hybrid resistance (M_H) and fungicide treatment (M_F). With these factors included, equation 3 becomes:

$$t_n = t_s M_M M_T M_D M_H M_F \tag{4}$$

For reference conditions, $M_M = M_T = M_D = M_H = M_F = 1$.

Using the above relationships, CO_2 production for t hours for any conditions can be predicted using:

$$Y = 1.3(e^{0.006t/m} - 1) + 0.015t/m \tag{5}$$

where m is the combined multiplier

$$m = M_M M_T M_D M_H M_F \tag{6}$$

Estimation of M_T (Temperature Multiplier)

For 15.6 < T ≤ 49°C and M ≤ 19% (Steele, 1967; Thompson, 1972):

$$M_T = 32.3e^{-3.48(1.8T+32)/60} \tag{7}$$

For 15.6 < T ≤ 26.7°C and 19 < M ≤ 28%:

$$M_T = e^{-0.00493277 + (0.05\,(1.8T + 32) - 3)\,[\ell n\,(0.0795012 + 0.0123150M)]} \tag{8}$$

Note: Equation 8 was derived by author Steele in 1999 to eliminate a discontinuity in the M_T equations from Steele (1967).

For 15.6 < T ≤ 26.7°C and M > 28%:

$$M_T = e^{2.56683-0.0428628(1.8T + 32)} \tag{9}$$

Note: Equation 9 was derived by author Steele in 1999 to eliminate a discontinuity in the M_T equations from Steele (1967).

For 26.7 < T ≤ 49°C and 19 < M ≤ 28% (Steele, 1967; Thompson, 1972):

$$M_T = 32.3e^{-3.48(1.8T+32)/60} + \left[\frac{M-19}{100}\right] e^{0.61(1.8T-28)/60} \tag{10}$$

For 26.7 < T ≤ 49°C and M > 28% (Steele, 1967; Thompson, 1972):

$$M_T = 32.3e^{-3.48(1.8T+32)/60} + 0.09e^{0.61(1.8T-28)/60} \tag{11}$$

For 0 ≤ T ≤ 15.6° C (Saul, 1970; Thompson, 1972):

$$M_T = 128.389e^{-4.86(1.8T+32)/60} \tag{12}$$

Note: Equation 12 is printed incorrectly in Thompson (1972).

Estimation of M_M (Moisture Multiplier) (Steele, 1967; Thompson, 1972)

For 13 ≤ M ≤ 35%:

$$M_M = 0.103\left[e^{\left(455/(100M/(100-M))^{1.53}\right)} - 0.845\,M/(100-M) + 1.558\right] \tag{13}$$

Note: Equation 13 is converted to wet basis moisture, whereas the equations in Steele (1967) and Thompson (1972) use dry basis moisture.

Estimation of M_D (Damage Multiplier) (Steele, 1967)

For 2 ≤ D ≤ 41% (Steele, 1967):

$$M_D = 2.08e^{-0.0239D} \tag{14}$$

From equation 14, M_D ranges from 2 (for D = 2%) to 0.78 (for D = 41%). Ng et al. (1998) observed mechanical damage to have a lesser effect on deterioration and defined an equation where M_D varies from 1.3 to 0.97 over this same range of D.

Estimation of M_H (Genetic Hybrid Multiplier) (Friday et al., 1989; Stroshine and Yang, 1990; Al–Yahya et al., 1993; Wilcke et al., 1993)

$$M_H = 1 \text{ for generic hybrid} \tag{15}$$

$$M_H = 1.25 \text{ for a resistant hybrid such as FR35×FR20} \tag{16}$$

$$M_H = 0.91 \text{ for a susceptible hybrid such as DF20 × DF12} \tag{17}$$

(T = 20°C, 18 ≤ M ≤ 24%, D = 3%)

Estimation of M_F (Fungicide Multiplier) (Al–Yahya et al., 1993; Wilcke et al., 1993)

$$M_F = 1 \text{ for no fungicide application} \tag{18}$$

$$M_F = 1.2 \text{ for corn treated with 20 ppm iprodione} \tag{19}$$

$$(T = 20°C,\ 18 \le M \le 24\%,\ 3 \le D \le 30\%)$$

$$M_F = 1.1 \text{ for corn treated with 80–ppm soybean oil} \tag{20}$$

$$(T = 20°C,\ M = 22\%,\ D = 3\%)$$

Equation 4 can be used to calculate corn storage times to any DML loss level for any selected combination of values of T, M, D, M_H, and M_F within the specified ranges. Table 1 shows predicted days of storage time for 0.5% DML for corn moistures from 16 to 34%, and corn temperatures from 2 to 49°C. Tabled values assume M_D = 1 (D = 30%), and M_H = M_F = 1.

Table 2 lists multipliers that can be applied to table 1 values to calculate times for other DML levels.

An example shows how to use the tables.

Example: Shelled corn at 20% moisture is stored at 10°C. What is the storage time for 0.5% DML? For 0.75% DML?

In the absence of additional information, the corn is assumed to have 30% by weight of kernels with mechanical damage (D = 30, M_D = 1), to be a generic hybrid (M_H = 1), and to be without fungicide treatment (M_F = 1). From table 1, the estimated time for 0.5% DML is 64 days. From table 2, the multiplier for 0.75% DML is 1.30. Using this multiplier, the time for 0.75% DML is calculated:

(1.30)(64days) = 83 days.

These times can also be calculated using equations:

- Noting that 1% DML corresponds to 14.66 g CO_2/kg original DM, calculate that 0.5% DML corresponds to 7.33 gCO_2/kg original DM, and 0.75% DML corresponds to 11.0 gCO_2/kg original DM.

Table 1. Shelled corn storage time for 0.5% dry matter loss, days.[a]

Corn Temp.		Corn Moisture (%)									
°C	°F	16	18	20	22	24	26	28	30	32	34
1.7	35	1144	437	216	128	86	63	50	41	35	31
4.4	40	763	291	144	85	57	42	33	27	24	21
7.2	45	509	194	96	57	38	28	22	18	16	14
10.0	50	339	130	64	38	26	19	15	12	10	9
12.8	55	226	86	43	25	17	13	10	8	7	6
15.6	60	151	58	29	17	11	8	7	5	5	4
18.3	65	113	43	22	13	9	7	5	4	4	3
21.1	70	85	32	16	10	7	5	4	4	3	3
23.9	75	63	24	12	8	5	4	3	3	2	2
26.7	80	47	18	9	6	4	3	3	2	2	2
29.4	85	35	14	7	5	3	3	2	2	2	1
32.2	90	26	10	5	4	3	2	2	2	1	1
35.0	95	20	8	4	3	2	2	2	1	1	1
37.8	100	15	6	3	2	2	2	2	1	1	1
40.6	105	11	4	3	2	2	2	1	1	1	1
43.3	110	8	3	2	2	2	1	1	1	1	1
46.1	115	6	2	2	2	1	1	1	1	1	1
48.9	120	5	2	1	1	1	1	1	1	1	1

[a] D = 30%, $M_D = M_H = M_F = 1$.

Table 2. Multipliers to allow calculation of times to other dry matter loss levels from table 1 values.

Dry Matter Loss (%)	Table 1 Multiplier
0.25	0.59
0.50	1.00
0.75	1.30
1.0	1.53

- Using equation 2, calculate that t_s = 230 h for 0.5% DML, and 299 h for 0.75% DML.
- Using equation 4 with equation 13 for M_M, equation 12 for M_T , equation 14 for M_D (M_D must be calculated to four significant figures to match the computer–calculated table values for storage time) and M_H = M_F = 1, t_n can be computed, in turn, for t_s = 230h and 299 h:
- for 0.5% DML: t_n = (230)(2.945)(2.237)(1.015)(1)(1) = 1538h = 64 days
- for 0.75% DML: t_n = (299)(2.945)(2.237)(1.015)(1)(1) = 1999h = 83 days

Conclusions

Equations 2 through 20 can be used to predict CO_2 production and storage time for a selected matter loss from shelled corn with 15 ≤ M ≤ 34%, 0 ≤ T ≤ 49°C, and 2 ≤ D ≤ 41%, and accounting for genetic susceptibility to spoilage and fungicide application. Table 1 contains predicted corn storage times for 0.5% DML, for a generic hybrid, without fungicide treatment, having 30% of kernels with visible mechanical damage. Table 2 multipliers allow calculation of projected storage times for 0.25, 0.75, and 1.0% DML. Note that all of the projected times are for constant and equilibrium aerated conditions.

References

Al–Yahya, S. A., C. J. Bern, M. K. Misra, and T. B. Bailey. 1993. Carbon dioxide evolution of fungicide–treated high–moisture corn. *Transactions of the ASAE* 36(5): 1417–1422.

Brooker, D. B., F. W. Bakker–Arkema, and C. W. Hall. 1992. *Drying and Storage of Cereal Grains and Oilseeds*. New York: Van Nostrand Reinhold.

Friday, D. C., J. Tuite, and R. Stroshine. 1989. Effect of hybrid and physical damage on mold development and carbon dioxide production during storage of high–moisture shelled corn. *Cereal Chemistry* 66(5): 422–426.

Gupta, P., W. F. Wilcke, R. V. Morey, and R. A. Meronuck. 1999. Effect of dry matter loss on corn quality. *Applied Engineering in Agriculture* 15(5): 501–507.

Hunt, D. 1995. *Farm Power and Machinery Management*, 9th Ed. Ames, Iowa: Iowa State University Press.

Jones, D. D., and R. D. Grisso. 1995. Holding wet corn with aeration. Neb Guide G87–862–A. University of Nebraska, Lincoln, Nebr.

Loewer, O. J., T. C. Bridges, and R. A. Bucklin. 1994. *On–Farm Drying and Storage Systems*. St. Joseph, Mich.: ASAE.

MWPS. 1983. Structures and environment handbook. MWPS–1. Midwest Plan Service, Iowa State University, Ames, Iowa.

_____. 1987. Grain drying, handling and storage handbook. MWPS–13. Midwest Plan Service, Iowa State University, Ames, Iowa.

Ng, H. F., W. F. Wilcke, R. V. Morey, R. A. Meronouk, and J. P. Lang. 1998. Mechanical damage and corn storability. *Transactions of the ASAE* 41(4): 1095–1100.

Saul, R. A. 1970. Deterioration rate of moist shelled corn at low temperatures. ASAE Paper No. 70302. St. Joseph, Mich.: ASAE.

Saul, R. A., and J. L. Steele. 1966. Why damaged shelled corn costs more to dry. *Agricultural Engineering* 47(6): 326–329.

Steele, J. L. 1967. Deterioration of damaged shelled corn as measured by carbon dioxide production. Ph.D. Thesis. Iowa State University, Ames, Iowa.

Steele, J. L., R. A. Saul, and W. V. Hukill. 1969. Deterioration of shelled corn as measured by carbon dioxide production. *Transactions of the ASAE* 12(5): 685–689.

Stroshine, R. L., and X. Yang. 1990. Effects of hybrid and grain damage on estimated dry matter loss for high–moisture shelled corn. *Transactions of the ASAE* 33(4): 1291–1298.

Thompson, T. L. 1972. Temporary storage of high–moisture shelled corn using continuous aeration. *Transactions of the ASAE* 15(2): 333–337.

Wilcke, W. F., R. A. Meronuck, R. V. Morey, H. F. Ng, J. P. Lang, and D. Jiang. 1993. Storage life of shelled corn treated with a fungicide. *Transactions of the ASAE* 36(6): 1847–1854.

Nomenclature

D = % by weight of mechanically–damaged kernels, which are kernels with visible ruptures or breaks in the seed coat
DM = dry matter
DML = dry matter loss
M = moisture content (% wet basis)
M_D = damage multiplier
M_F = fungicide multiplier
M_H = hybrid multiplier
M_M = moisture multiplier
M_T = temperature multiplier
m = multiplier accounting for all conditions in the carbon dioxide evolution equation
T = corn temperature (°C)
t = time (h)
t_n = time (h) under non–reference conditions
t_s = time (h) under reference conditions of T = 15.6°C, M = 25%, D = 30%
Y = g CO_2 per kg dry matter