

A Model of Alfalfa Hay Storage

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ABSTRACT

ALFAFA hay baled at various moisture contents and densities was placed into storage where dry matter loss, temperature and quality changes were measured. A two-way analysis of variance indicated that baling moisture ($p < 0.01$) and moisture times density ($p < 0.02$) significantly affected dry matter loss; storage temperatures were positively correlated with moisture and density ($p < 0.01$). Sensible heat generation rate during the first 30 days in storage was affected by baling moisture, density and moisture times density ($p < 0.0001$).

From the data, semitheoretical models predicting storage changes in alfalfa hay were developed and validated. Dry matter loss was a function of the sensible heat generated and moisture lost during storage. A finite difference heat transfer model and storage temperature data were used to estimate heat generation rate over time. The rate increased during the first several days of storage and decreased thereafter.

Total amounts of acid detergent fiber and ash did not change during storage; however, concentration increases occurred due to loss of non-fiber, non-ash dry matter. Crude protein loss was 40% of that of other dry matter which resulted in a small increase in protein concentration. The amount of acid detergent insoluble protein increased in proportion to the degree days for which stack temperature exceeded 35°C.

INTRODUCTION

Stable storage of alfalfa hay in rectangular bales requires the hay to contain less than 18% moisture (Ohm et al., 1971). During field curing, considerable losses in dry matter and nutrient value occur due to respiration, leaching, bleaching, microbial activity and mechanical handling (Savoie et al., 1982). Hay baled at a moisture content above 18% will have less field loss; however, this hay will heat during storage causing dry matter loss and nutrient degradation (Miller et al., 1967; Moser, 1980). Spontaneous combustion can also occur causing a complete loss of the hay as well as the storage facility.

Research has evaluated alternative storage techniques

and chemical preservatives to safely increase the baling moisture of hay (Davies and Warboys, 1978; Johnson and McCormick, 1976; Knapp et al., 1975; Nehrir et al., 1978; Nelson, 1966, 1968, 1972; Shepherd et al., 1954; Weeks et al., 1975). This research has primarily compared two or more storage methods. When experiments are conducted and reported as comparative tests, results are not widely applicable. Research results in the form of models which accurately simulate the storage process would be more valuable for use in evaluating alternative methods for storing alfalfa hay over a wide range of conditions.

Storage dry matter loss in baled hay is a function of baling moisture, maturity, bale density, and the type of storage facility. Dry matter is lost when there is sufficient moisture for microbial activity (Ohm et al., 1971). Research has indicated a correlation between baling moisture and dry matter loss (Nelson, 1966, 1968, 1972). For hay stored in isolated chambers, the primary factors affecting dry matter loss were moisture and maturity whereas bale density had no effect (Nelson, 1966, 1968). Martin (1980) suggested that hay loses 5 to 10% dry matter if baled at less than 20% moisture. Waldo and Jorgensen (1981) suggested a rule of thumb: 1% loss in dry matter for each 1% decrease in moisture content during storage.

If hay is baled at a low moisture level and stored inside, few nutrient changes occur during storage (Moser, 1980). Weeks et al. (1975) reported little chemical change in loosely stacked hay harvested at up to 40% moisture. Other research indicates that when hay is baled at moisture levels exceeding 20%, heating and mold development occur which affect nutrient retention (Miller et al., 1967). Several researchers reported significant quality changes during storage when baling moisture was above 20% (Miller et al., 1967; Nehrir et al., 1978; Nelson, 1966, 1968).

The objective of this work was to determine the nutrient and temperature changes which occur in baled alfalfa hay during storage and to develop models which predict hay stack temperature, dry matter loss and changes in nutrient content during storage as functions of moisture content and density at the time of baling.

EXPERIMENTAL PROCEDURE

Three trials were conducted during 1985, one each from first, second, and third cutting alfalfa in East Lansing, MI. Alfalfa was cut with a 2.8 m wide mower-conditioner and laid in a 2.0 m wide swath to dry. Swaths were raked into windrows at different times so that treatments of different moisture levels could be baled at approximately the same time. All treatments within a trial were baled within 4 days of mowing.

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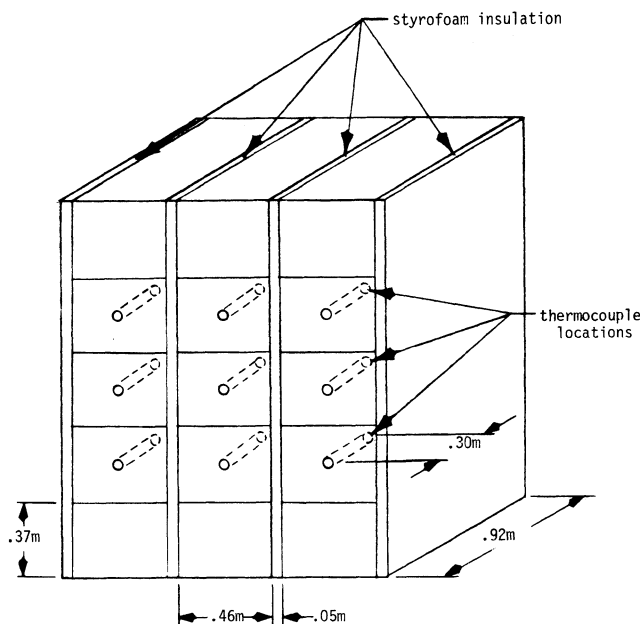


Fig. 1—Hay stack geometry.

The target treatments consisted of all combinations of six moisture levels (15, 20, 25, 30, 35, and 40% wet basis) and two density levels ($< 130 \text{ kg/m}^3$ and $> 160 \text{ kg/m}^3$, wet material). When the hay in the windrow was near a target moisture level, hay was baled at each density. Density was varied by adjusting the baler chamber pressure. Five bales of each treatment which appeared uniform in moisture and density were monitored during storage.

Initial sampling was performed within 2 h of baling. Samples (40g) were obtained by coring from the end toward the center of a bale with a 2.5 cm diameter boring tool. For determination of moisture content, three bales per treatment were sampled; individual bale samples were dried in an oven at 60°C for 72 h. Additional core

samples from each of the five bales were combined to form a composite sample for quality analysis. Quality samples were dried at 20°C in a convective oven for at least 24 h. Standard laboratory procedures were used to determine crude protein (CP) and ash contents (A.O.A.C., 1960). Acid detergent fiber (ADF), and acid detergent insoluble protein (ADIP) contents were determined by the methods of Goering and Van Soest (1970).

After samples were collected, bales were weighed and measured. Initial dry matter was the product of the mean dry matter content for the treatment and individual bale mass. Bale density was determined as bale mass (dry matter plus water) divided by bale volume where volume was estimated as bale length times the cross sectional area of the baler chamber (36.8 cm x 45.7 cm).

Following initial sampling, bales were stacked in a barn 5 bales high. Treatments were stacked adjacent to one another separated by a sheet of styrofoam 5.0 cm thick. Thermocouples were placed in the three center bales of each treatment stack along the center line of the bales and approximately 30 cm into the bale (Fig. 1). Bale temperatures were recorded every 6 h for the first 30 days of storage. Bales were removed from storage and the sampling process was repeated approximately 60 days after baling.

EXPERIMENTAL RESULTS

The target hay treatments (i.e., moisture and density combinations) were not always obtained; however, a wide range of treatments was obtained. Actual moisture contents and densities measured are reported in Tables 1 and 2 along with measured temperature and loss values.

Dry matter loss during storage varied from 1 to 20% and was positively correlated with moisture content at baling, bale density, maximum and mean storage temperatures and heating in degree days above 35°C ($p < 0.01$). A two-way analysis of variance of dry matter loss by baling moisture and density indicated that baling moisture was the most significant factor affecting dry matter loss ($p < 0.01$); the product of baling moisture and density was less significant ($p < 0.02$) and density was least significant ($p < 0.10$).

Maximum and mean storage temperatures and

TABLE 1. Dry Matter Loss, Temperature and Heating During Storage of Alfalfa Hay Baled at Various Moisture and Density Levels

Baling Moisture range, % w.b.	Number of stacks	Mean baling moisture, % w.b.	Density, kg/m ³	Dry matter loss, %	Temperature		Heating, degree days> 35°C	Heat Generation rate*, W/kg
					Maximum °C	Mean† °C		
10-15	1	11.5	111	2.1	25.9	18.6	0	0.0040
	2	14.4	173	2.5	24.9	18.3	0	0.0004
15-20	5	17.7	87	3.1	26.2	20.8	0	0.0109
	3	16.8	188	3.0	36.7	25.3	10	0.0329
20-25	3	24.0	101	4.4	29.0	18.0	1	0.0077
	2	22.4	227	4.4	42.6	28.5	34	0.0880
25-30	1	27.7	106	5.8	28.6	21.0	0	0.0546
	2	26.4	230	9.4	47.0	33.7	110	0.1299
30-35	5	32.7	154	9.7	42.5	24.9	44	0.1262
	3	31.2	279	9.1	48.0	34.0	148	0.1313
35-40	0							
40-50	3	36.1	292	12.2	53.6	39.4	238	0.2066
	1	48.0	189	17.8	59.7	30.6	169	0.1962
	1	43.0	302	19.5	62.4	41.5	354	0.2219
10-50	32	24.6	180	7.1	39.1	26.6	69	0.0854

* Mean rate of sensible heat generation over the first 30 days of storage.

† Mean temperature over first 30 days of storage.

TABLE 2. Initial Quality and Storage Quality Retention Ratios for Alfalfa Hay Baled at Various Moisture Contents and Stored for 60 Days

Baling moisture range, % w.b.	Number of observ.	Quality as placed into storage*				Quality retention ratio†			
		Ash %	ADF %	CP %	ADIP %	Ash	ADF	CP	ADIP
10-15	3	7.2	42.5	13.9	1.13	1.04	0.92	1.07	0.99
15-20	8	8.3	34.3	17.0	1.01	0.99	0.99	0.99	1.02
20-25	5	8.9	31.2	20.1	1.07	1.02	1.06	0.97	1.13
25-30	3	8.2	37.5	15.3	1.12	1.00	0.95	1.05	1.20
30-35	8	8.9	33.4	19.3	1.20	0.98	1.00	0.96	1.21
35-40	3	9.5	34.6	20.0	1.22	1.01	1.01	0.96	1.78
40-50	2	8.2	38.2	16.4	1.14	1.00	1.04	0.88	2.14
10-50	32	8.6	33.7	17.9	1.12	1.00	1.00	0.98	1.20

* ADF = Acid Detergent Fiber, CP = Crude Protein, ADIP = Acid Detergent Insoluble Protein, expressed as % of dry matter.

† Total amount out of storage / Total amount into storage.

heating in degree days above 35°C were each positively correlated with baling moisture and density ($p < 0.01$). Mean heat generation rate for the first 30 days in storage was affected by baling moisture, density and the product of baling moisture times density ($p < 0.0001$).

Increased baling moisture resulted in an increase in the concentrations of crude protein (CP), ash and acid detergent fiber (ADF) of hay when removed from storage. Quality retention ratios (Table 2) indicated that the total amount of ash and ADF remained constant during storage, while some CP was lost. The amount of acid detergent insoluble protein (ADIP) in hay as removed from storage increased with baling moisture because high storage temperatures, which lead to bound protein, were associated with high baling moisture.

HEAT TRANSFER ANALYSIS

Finite Difference Model

A model was developed to predict temperatures over time in stored alfalfa hay. Heat transfer in hay stacks was assumed to be entirely by conduction. Moisture loss from hay during storage complicates the heat transfer process because moisture loss may change thermal properties. To include changing property effects, a numerical solution was necessary. The explicit finite difference approach was chosen for this application because of its simplicity and ease in predicting heat generation rate from temperature data. Explicit finite difference equations for determining temperature in a body are found in many textbooks; however, most do not include a heat generation term. The inclusion of internal heat generation resulted in the following explicit equation for updating temperatures at internal nodes in a 2-dimensional body:

$$T_{j,l,p+1} = (\alpha \Delta t / (\Delta x^2)) (T_{j+1,l,p} + T_{j-1,l,p} + T_{j,l+1,p} + T_{j,l-1,p} - 4T_{j,l,p}) + (\alpha \Delta t / k) g + T_{j,l,p} \quad \dots \dots \dots [1]$$

Equation [1] holds for grids with equal increments in the x and y directions (i.e., $\Delta x = \Delta y$). Similar equations were developed for nodes along the boundary of the hay stack.

Thermal Property Estimation

In order to use the heat transfer model, thermal properties of hay were required. These properties of hay have not been well defined. Jiang et al. (1986) developed regression formulas for estimating thermal properties of haylage as functions of moisture content and density; their formulas were not directly applicable for this work since the ranges of moisture and density were quite different.

Thermal diffusivity was calculated from specific heat and thermal conductivity. Specific heat was estimated on a mass fraction basis with contributions from water and dry matter (Pitt, 1983):

$$c = 4180 m + 1890(1-m) \quad \dots \dots \dots [2]$$

Pitt (1983) proposed that thermal conductivity be computed on a volume fraction basis with contributions from air and herbage. This required the assumption that the conductivity of herbage was equal to that of water.

Based on the data of Jiang et al. (1986), this approach is insufficient. For this work, thermal resistance (inverse of conductivity) was computed on a mass fraction basis with contributions from dry matter, air and water:

$$k = \frac{1}{X_{dm}/k_{dm} + X_a/k_a + X_w/k_w} \quad \dots \dots \dots [3]$$

Based on the data of Jiang et al. (1986), the thermal conductivity of forage dry matter is approximately 0.144 W/m°C. Thermal conductivities of air and water are readily available.

Thermal properties throughout storage were determined using measured initial and final moisture contents, density and an assumed drying curve. The drying curve was modeled as exponential decay towards an equilibrium moisture content which is typical of biological products in the falling rate drying period (Brooker et al., 1974):

$$m(t) = m_{eq} + (m_i - m_{eq})e^{-bd} \quad \dots \dots \dots [4]$$

A value of 0.12 was used for equilibrium moisture content, and the drying constant was computed using measured initial and 30-day moisture contents.

Heat Generation Rate Estimation

With the finite difference heat transfer model and estimated thermal properties, sensible heat generation rate was determined. Equation [1], the expression for estimating temperatures at an internal node, was solved for the heat generations rate term, g^* :

$$g = [T_{j,l,p+1} - T_{j,l,p} - (\alpha \Delta t / (\Delta x^2)) (T_{j+1,l,p} + T_{j-1,l,p} + T_{j,l+1,p} + T_{j,l-1,p} - 4T_{j,l,p})] k / (\alpha \Delta t) \quad \dots \dots \dots [5]$$

Time/temperature data was collected for three locations in the small hay stacks. Data were averaged to give one temperature value per treatment per day to reduce error caused by random variation. Since styrofoam insulation was used to separate the stacks (Fig. 1), temperature variations were assumed to be zero in one horizontal direction. The boundary conditions were (a) natural convection on the top surface, (b) natural convection on the end, (c) insulation on the bottom surface, and (d) insulation at the center of the bale by symmetry.

Fig. 2 illustrates the numerical procedure used to estimate heat generation rate. For a given day, sensible heat generation rate was calculated using equation [5], immediate past temperatures ($T_{j,l,p}$, $T_{j-1,l,p}$, $T_{j+1,l,p}$, $T_{j,l-1,p}$, $T_{j,l+1,p}$) and the target temperature ($T_{j,l,p+1}$) for the next day. Past temperatures were determined using the finite difference model and heat generation rates of previous days. The target temperature for the next day was determined from experimental data. The procedure was repeated for the equivalent of 30 days with ambient and target temperatures and thermal properties updated daily. The grid increment, Δx , was set as 0.153 m, and the time increment, Δt , was set at 1800 s.

*Heat generation rate as used in this context is not all inclusive. Heat used to evaporate moisture from the hay is not included.

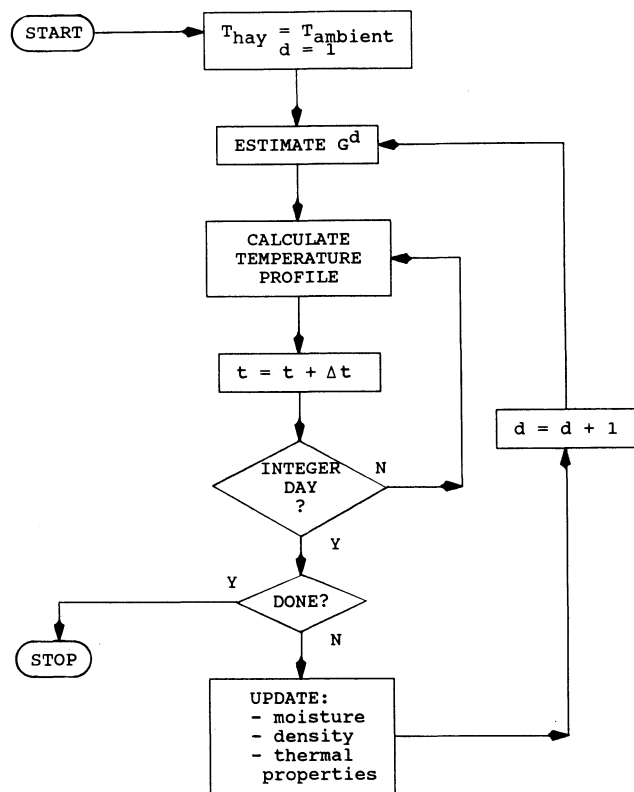


Fig. 2—Flowchart of procedure used to estimate heat generation rate (G) over time (d is time in integer days).

MODEL DEVELOPMENT

Sensible Heat Generation Rate

Prediction of hay temperature and dry matter loss during storage requires a model for predicting sensible heat generation rate. The heat transfer analysis gave 960 cases (32 stacks x 30 days each) of heat generation rate for different moisture contents, densities and times from baling. Nonlinear regression was used to fit an exponential model to these data where the exponents of moisture and density were constant.

A plot of heat generation rate over time indicated that not only was time a significant factor, but the time course of heat generation rate was not monotonic. The rate increased during the first several days and decreased thereafter. Time raised to a constant power would not fit this data; therefore, the data was split into two sets corresponding to $d \leq 9$ and $d \geq 9$, respectively.

The heat generation process involves biological activity which is influenced by temperature; even so, temperature was excluded from this model to simplify estimation of mean heat generation rate and dry matter loss and to allow heat generation to be solely a function of bale parameters.

The model for sensible heat generation rate per unit mass was:

for $d < 9$:

$$G = 0.064(m_i)^{2.18}(\rho_i)^{0.5}d^{0.53} \quad (R^2 = 0.53)$$

..... [6a]

for $d > 9$:

$$G = 0.34(m_i)^{1.23}(\rho_i)^{0.94}d^{-1.8} \quad (R^2 = 0.43)$$

..... [6b]

for $d = 9$, the average of the two expressions was used. This model in combination with an appropriate heat transfer model can be used to simulate temperature in hay stacks of any size or shape. The heat generated can be found by integrating equations [6a] and [6b] over the desired time interval. Sensible heat generated in a hay stack stored 6 months is:

$$Q = 104.0(m_i)^{2.18}(\rho_i)^{0.5} + 5.72(m_i)^{1.23}(\rho_i)^{0.94}$$

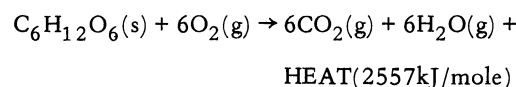
..... [7]

Dry Matter Loss

Empirical models which predict storage dry matter loss from parameters such as baling moisture and density can be useful, but they may not be applicable if conditions change. To obtain a more generic model, dry matter loss was related to the amount of sensible heat generated during storage by considering an energy balance on the hay stack. Heat generated during storage dries the hay, raises hay temperature or is lost to the environment:

$$q_t = q_{ev} + q_{tr} + q_{env} \quad \dots\dots\dots [8]$$

Heat generation can only occur with organic material serving as a source of energy. The energy source in baled hay is primarily carbohydrate. The chemical reaction for the respiration of glucose or fructose is:



where the carbohydrate (glucose) is in solid form and the oxygen, carbon dioxide and water are in gaseous form. The total heat produced in a stack of hay is the amount of dry matter consumed times the energy content of that dry matter:

$$q_t = M(2557 \text{ kJ/mole carbohydrate}) / (1 \text{ mole carbohydrate} / 0.18 \text{ kg})$$

$$= 14206M \quad \dots\dots\dots [9]$$

The amount of dry matter lost in a hay stack can be calculated from initial moisture and dry matter loss as a percent of initial dry matter:

$$M = \rho VL(1 - m_i) \quad \dots\dots\dots [10]$$

Moisture removal requires heat; the amount of heat required for moisture evaporation can be computed by multiplying the amount of water lost times the heat of vaporization of water:

$$q_{ev} = \rho V(m_i - m_f(1 - m_i)(1 - L) / (1 - m_f))H_w \quad \dots\dots [11]$$

($H_w = 2433 \text{ kJ/kg}$ at 25°C). Assuming initial and final hay temperatures are equal ($q_{tr} = 0$), the net heat

transferred from a stack to its environment during storage is the difference between total heat production and heat used for water evaporation.

Recall that the heat generation rate analysis outlined in previous sections does not account for heat used to evaporate moisture (although thermal properties were estimated with evaporation considered). The derived sensible heat generation rate, therefore, is for heat released from the hay stack. Sensible heat transferred from the stack to its environment during a storage period is:

$$q_{env} = \rho V Q \quad \dots \dots \dots [12]$$

A theoretical equation for dry matter loss as a function of initial and final moisture contents and heat generated can be obtained by combining equations [8] thru [12] and solving for dry matter loss:

$$L = \frac{Q + 2433(m_i - m_f(1-m_i)/(1-m_f))}{(1 - m_i)(14206 - 2433 m_f/(1 - m_f))} \quad \dots \dots \dots [13]$$

Quality Changes

Dry matter lost during storage was primarily soluble carbohydrate with some loss of protein. The total amount of ash, therefore, remains constant during storage. The concentration increased because of the loss of other dry matter:

$$ASH_f = \frac{ASH_i}{(1-L)} \quad \dots \dots \dots [14]$$

Similarly, since ADF components are not lost during hay storage, an increase in ADF concentration is obtained. An increase in acid detergent insoluble protein would also increase ADF content; however, this change is on the order of 0.2% dry matter and can be neglected as an increase in ADF.

$$ADF_f = \frac{ADF_i}{(1-L)} \quad \dots \dots \dots [15]$$

Microorganisms may consume some protein as well as carbohydrate; however, since carbohydrate is the primary energy source for the organisms, CP is consumed at a lower rate. To determine a function for the change in CP, regression was used to fit our experimental data to a model expressing total CP loss as a fraction of total dry matter loss:

$$CP_f = \frac{CP_i(1 - \beta(L))}{(1-L)} \quad \dots \dots \dots [16]$$

Crude protein loss was determined to be about 40% of the loss of other dry matter, i.e. $\beta = 0.4$ ($r = 0.4$).

A factor which affects protein availability in hay is protein bound to fiber when excessive heating occurs. Our experimental data indicated the total amount of ADIP increased in proportion to heat accumulation in the stack measured by degree days above 35°C (HDD). Linear regression analysis provided the following model for $HDD < 400^\circ C - \text{days}$:

$$ADIP_f = \frac{(ADIP_i + 0.00373HDD)}{(1-L)} \quad \dots \dots \dots [17]$$

Heat accumulation (HDD) is a function of size and shape of the hay stack as well as the amount of heat generated in the hay.

MODEL VALIDATION

Heat Generation and Temperature Prediction

For validation, the heat generation model was used in combination with an explicit three dimensional finite difference model to predict storage temperatures in five 40-bale stacks of hay stored in 1986. These stacks had initial moisture contents of 24.4, 19.3, 25.1, 21.7 and 28.2%. Storage temperatures were measured for 30 days at 12 locations within each stack. The temperatures were averaged to give a daily "mean" stack temperature. Simulated temperatures for the same locations were averaged in the same manner. These daily mean stack temperatures, as well as temperatures at the location nearest the center of the stack were used for validation.

A linear regression of experimental time-temperature data versus predicted time/temperature data was used to investigate model validity. The null hypotheses for testing model validity were that the intercept and slope were different from 0.0 and 1.0 respectively. Using the students t-test with n-2 degrees of freedom, the null hypotheses were not rejected at any level; this procedure indicated an invalid model for temperature prediction (Table 3, Fig. 3). Investigation of residuals between predicted and actual temperatures showed that most of the error occurred after the twentieth day of storage. For the interval between days 20 and 30, predicted mean stack temperatures exceeded actual temperatures by as much as 10°C. During this time period, most heat generation is past and the stack is cooling towards ambient temperature. The over prediction of temperatures during this period indicates an error in

TABLE 3. Validation of the Storage Model Through Linear Regression of Actual Measurement vs. Predicted

Parameter tested	No. of cases	Slope value	Slope SE	Intercept value	Intercept SE	r ²	r ² _{0,1}
Temperature†	132	1.34*	0.07	-12.40**	2.1	0.76	0.63
Temperature‡	132	1.20*	0.06	-9.30**	2.0	0.76	0.64
Dry Matter Loss	5	1.94	0.66	-4.90	3.4	0.82	0.56
Dry Matter Loss§	8	1.27	0.35	-1.40	2.8	0.79	0.63
Acid Detergent Fiber	72	0.93	0.06	1.50	2.2	0.80	0.67
Ash	32	0.82*	0.06	1.60**	0.5	0.96	0.88
Crude Protein	100	0.98	0.06	-0.27	1.2	0.91	0.70
Acid Detergent Insoluble Protein	10	0.63	0.17	0.45	0.2	0.89	0.42

A slope of 1.0 and intercept of 0.0 indicates a valid model.

* Different from 1.0 (p=0.05)

** Different from 0.0 (p=0.05)

† Means of 12 stack temperatures over time

‡ Temperatures at a location near the stack center over time

§ Actual loss data from Davies and Warboys (1978), Knapp et al. (1975) and Nehrir et al. (1978).

SE = standard error of the respective regression coefficient

r² = coefficient of determination

r²_{0,1} = coefficient of determination for a line of zero intercept and slope of 1.0.

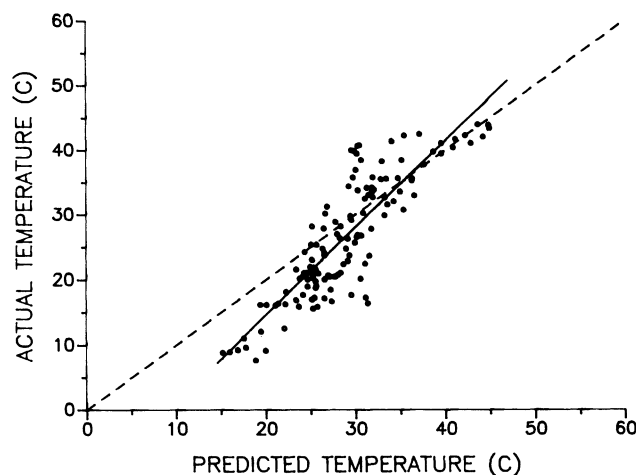


Fig. 3—Actual vs. predicted temperatures for five, 40 bale stacks of hay (means over 12 locations within the stacks).

thermal property estimation (most likely thermal conductivity).

The coefficients of determination (r^2) for actual versus predicted temperatures for a line of zero intercept and slope of 1.0 were 0.63 and 0.64 for the mean stack and center temperatures, respectively (Table 3, Fig. 3). Although the slope/intercept test indicated an invalid model, considering the complexity of the problem, explanation of 63 to 64% of all variation in hay stack temperatures was considered satisfactory.

The temperature model predicted maximum stack temperature very well with the largest error being -5.5°C and the average error $+0.4^\circ\text{C}$. The model was adequate for estimating temperatures during the heating period but more work on thermal properties of baled forages is needed so complete time/temperature relationships can be predicted.

As a qualitative test, temperatures in stacks of 1000 bales were modeled. With typical bale densities ($128\text{--}174\text{ kg/m}^3$), predicted maximum storage temperatures for hay baled at 12, 15, 18, 21 and 22.5% moisture were 38, 47, 57, 69 and 76°C respectively. Moser (1980) suggests very little nutrient loss in hay when temperatures are less than 60°C . In the current analysis, this peak temperature corresponds to moisture contents below 20%. As temperatures exceed 70°C , losses in digestibility and protein availability are very high and spontaneous combustion is possible (Martin, 1980). With the current model, these problems occur with moisture contents of 22% or greater. These predicted moisture levels correspond closely to those commonly accepted as necessary for stable hay storage.

Dry Matter Loss

Validation of the dry matter loss model was carried out using the same 40-bale stacks. The predicted storage losses in each of the five stacks were 5.2, 2.8, 5.7, 4.1 and 6.9%; the actual storage losses were 4.1, 1.8, 4.0, 2.9 and 10.8% respectively. A linear regression of actual versus predicted loss is included in Table 3. The regression results indicate a valid model ($p < 0.05$).

The dry matter loss model (equations [7] and [13]) was also used to predict storage losses for comparison to values published by Davies and Warboys (1978), Knapp

et al. (1975) and Nehrir et al. (1978). Since the published data did not include bale densities nor final moisture contents, predictions were based on published initial moisture contents, a final moisture content of 0.12 and typical densities estimated using data from this study. Linear regression analysis of the reported losses versus predicted losses indicated a valid model (Table 3).

Quality Changes

The quality models (equations [14] to [17]) were validated using data collected during hay preservation experiments conducted over the 1984, 1985 and 1986 hay seasons (Rotz et al., 1988). Experimental procedures for hay storage were similar to those described in the procedure section of this paper except treatment stacks contained 10 bales. The number of treatments used to validate each model varied depending upon available data and ranged from 10 to 100. Linear regression results of actual versus predicted quality characteristics are included in Table 3.

Comparisons of the intercept and slope of the regression line for ADF to 0.0 and 1.0 respectively indicated a valid model ($p < 0.05$). Of the variation in the validation data, 67% was explained by the model. Although the ash model was invalid using the same slope/intercept hypotheses, the model explained 88% of the variation in the data.

The crude protein model was shown to be valid ($p < 0.05$) using the slope/intercept hypotheses and explained 70% of all variation in the validation data set. The ADIP model was also valid ($p < 0.05$) even though only 42% of all variation was explained. Different laboratories performed the quality analysis in the experiments from which the validation data were obtained, thus some inaccuracy may be due to laboratory differences.

CONCLUSIONS

Analysis of bale temperatures using a finite difference heat transfer model indicated that sensible heat generation rate in rectangularly baled alfalfa hay was positively correlated with moisture and density. The rate increased during the first several days of storage and decreased thereafter. An empirical model of heat generation rate was developed from the experimental data. The model was integrated over a 6 month storage period to obtain an equation which predicts sensible heat generation as an exponential function of the initial moisture content and density of hay.

An energy balance applied to a hay stack resulted in a theoretical model where dry matter loss is a function of sensible heat generated and moisture lost during storage. Dry matter loss consisted of carbohydrate and crude protein with crude protein loss being 40% of that of carbohydrate. The total amounts of acid detergent fiber and ash did not change during storage so concentrations increased as other constituents were lost. The amount of acid detergent insoluble protein increased in proportion to heating in degree days above 35°C .

The validity of models for stack temperature, dry matter loss and quality change was determined by comparing predicted data to actual data measured in independent experiments. Reasonably good comparisons were found with all models when actual versus predicted data were compared to a line of zero intercept and slope

of 1.0. Coefficients of determination were generally greater than 0.6 so most models explained at least 60% of the variation in actual data.

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NOMENCLATURE

Parameters:

ADF	= acid detergent fiber content, percent of dry matter
ADIP	= acid detergent insoluble protein content, percent of dry matter
ASH	= ash content, percent of dry matter
α	= thermal diffusivity, m^2/s
b	= drying constant, 1/days
c	= specific heat, J/kg °C
CP	= crude protein content, percent of dry matter
d	= time, days
g	= sensible heat generation rate, W/ m^3
G	= sensible heat generation rate, W/kg
H	= heat of vaporization, kJ/kg °C
HDD	= heat development, degree days > 35°C
k	= thermal conductivity, W/ m^2 °C
L	= dry matter loss, fraction of initial dry matter
m	= moisture content (wet basis), decimal
M	= mass of dry matter lost, kg
ρ	= density, kg/ m^3
q	= heat, kJ
Q	= total sensible heat generated, kJ/kg dry matter
Δt	= time increment, s
T	= temperature, °C
V	= volume, m^3
Δx	= grid increment, m
X	= mass fraction

Subscripts:

a	= air
dm	= dry matter
env	= environment
eq	= equilibrium
ev	= evaporation
f	= final
i	= initial
j	= node location in x direction, multiples of Δx
l	= node location in x direction, multiples of Δx
p	= time, multiples of Δt
t	= total
tr	= temperature rise
w	= water