THESIS

This is to certify that the

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HEAT GENERATION AND DRY MATTER LOSS
DURING STORAGE OF RECTANGULARLY BALED ALFALFA HAY

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Dennis R. Buckmaster

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C. Alan Rotz
Major professor

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HEAT GENERATION AND DRY MATTER LOSS DURING STORAGE OF RECTANGULARLY BALED ALFALFA HAY

By

Dennis R. Buckmaster

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ABSTRACT

HEAT GENERATION AND DRY MATTER LOSS
DURING STORAGE OF RECTANGULARLY BALED ALFALFA HAY

By

Dennis R. Buckmaster

Alfalfa hay is commonly stored in rectangular bales at a moisture content below 18 percent (w.b.). To properly evaluate the benefits of preservatives or other alternative management schemes used to increase this moisture limit, the biological process of storage must be thoroughly understood.

Dry matter loss in rectangularly baled alfalfa hay was empirically modeled as a function of moisture content at baling. Dry matter loss was increased 0.5 percent for each percent increase in baling moisture above 11.5 percent.

A finite difference heat transfer model was applied to stacks of baled alfalfa hay to determine heat generation rates. Mean heat generation rates over the first thirty days of storage ranged from 0.0 to 0.243 W/kg of hay material. Heat generation rate varied as the square of moisture content and the square root of density with a maximum rate occurring after approximately 8 days in storage.

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NOMENCLATURE

Symbol	Definition	Units
A	thermal diffusivity	m^2/s
B	simplifying constant (A*DT/K)	$m^3 {}^oC/W$
C	specific heat	J/Kg^oC
C_a	specific heat	KJ/Kg^oC
C_b	specific heat	Btu/lb^oF
C_c	specific heat	cal/gm^oC
D	density	--
D_d	dry matter density	Kg/m^3
D_w	wet density	Kg/m^3
DI_w	wet density at time of baling	Kg/m^3
DD	heating in degree days >35^oC	^oC*day
DT	time increment	s
DX	grid increment	m
DML	dry matter loss (% of initial)	%
F	Fourier modulus	--
FDM	final dry matter	Kg
G	heat generation rate	W/m^3
G2	heat generation rate	W/Kg
H_{evap}	heat required to evaporate water	KJ
H1	horizontal surface convective heat transfer coefficient	$W/m^2\ {}^oC$
H2	vertical surface convective heat transfer coefficient	$W/m^2\ {}^oC$
IDM	initial dry matter	Kg
K	thermal conductivity	(W/m^oC)
L	dry matter lost	Kg
M	moisture content (wet basis)	decimal
MI	moisture content at time of baling (wet basis)	decimal
m	moisture content (wet basis)	%
M_{30}	moisture content 30 days after baling	decimal
M_{60}	moisture content 60 days after baling	decimal
P	application rate of propionic acid (% of wet weight)	%
Q_{net}	heat leaving hay stack	KJ
r	Pearson Product Moment correlation coefficient	--
R	multiple correlation coefficient	--
t	time from baling	days
T_{max}	maximum hay temperature in storage	^oC

NOMENCLATURE (cont.)

Symbol	Definition	Units
T_{mean}	mean temperature during the first 30 days of storage	^oC
T_a	ambient temperature	^oC
$T_{i,j,p}$	temperature at: x node = i, y node = j, time = p*DT	^oC
THP	total heat production	KJ
V	volume	m^3
X	density	lb/ft^3
Y	thermal diffusivity	ft^2/h

1. INTRODUCTION

The ideal alfalfa hay handling system would 1) allow for convenient crop handling, 2) be inexpensive, 3) not allow material or dry matter loss, and 4) not allow quality deterioration. Numerous methods of storing alfalfa hay do exist, but the ideal storage system does not now exist. Stacks, round and rectangular bales of all sizes, pellets, and high density cubes are all used. In an effort to find an optimum storage method, much research has been conducted in the area of alfalfa hay storage systems. Because thermal and physical properties may vary significantly within a unit of stored hay, the study of changes during storage is far from an exact science.

Alfalfa hay storage research is usually conducted as a simultaneous comparison of two or more storage methods. As examples: 1) inside vs. outside storage, 2) stacks vs. rectangular bales, or 3) chemically treated bales vs. non-treated bales. Primary considerations in comparing such treatments have been dry matter loss and quality changes during the storage period. Because this type of research is usually performed as a comparison test, the results are simply comparisons of two or more methods. Conclusions drawn from experiments conducted in this manner are limited to the experimental conditions, i.e., a given moisture level and density, or fixed environmental conditions. In order for the results to be more applicable, models describing the changes in each storage method should be developed. Models of the storage process which accurately simulate the real situation would be valuable tools to use when evaluating alternative methods for harvesting and storing alfalfa hay.

One must remember that models are decision aids, not decision makers. Decision aids in the area of storing alfalfa hay would suggest correct answers to questions like: "Will change occur in the hay during the storage period?"; "Is the change beneficial?"; "Will any deterioration occur?"; or "Will the stored hay heat enough to cause a barn fire?". If the answers to all questions were a clear "yes" or "no", models would be unnecessary. It is the fact that the answers are "sometimes yes" and "sometimes no" that provides the motivation to describe the storage process. Useful models will not only indicate yes or no answers to such questions, but will also give quantitative information.

The research work of this study is not a comparison of storage systems or chemical treatments. It is, rather, an in-depth look at storage of alfalfa hay in standard rectangular bales. Quantity of material taken out of storage and heating during storage as affected by moisture level and density at the time of baling are discussed and appropriate models are developed.

2. OBJECTIVES

The objectives of the research were to describe the changes which occur to alfalfa hay in rectangular bales during storage. Specific objectives were:

1. To develop an empirical model which predicts dry matter loss during storage as a function of initial moisture content and density of the hay as it enters storage.
2. To develop an empirical model which predicts the heat generation rate of baled alfalfa while in storage as a function of moisture and density levels.
3. To model the heat transfer process throughout a stack of hay based upon assumed physical and thermal properties in order to apply information obtained from small hay stacks to stacks of any size and shape.

3. LITERATURE REVIEW

3.1 STORAGE OF ALFALFA HAY

There are many ways to store alfalfa hay. This discussion concerns only baled alfalfa hay stored in a barn in the conventional manner, i.e., without refrigeration or forced ventilation. For alfalfa stored in this manner, the term "safe storage" implies: 1) little heating of the stored hay, 2) no molding, and 3) no degradation of nutrients in the hay during the storage period. Safe storage of baled alfalfa is normally assumed if the baling moisture is lower than 20%; however, Hall (1980) reported that safe storage for 200 days requires a maximum of 15% moisture[1].

When alfalfa is cut, it contains 70 to 80% water. It can easily take up to 4 or 5 days for the hay to dry down to 15 - 18% moisture in the field. During this field curing, considerable respiration and leaching losses can occur. Hay which dries slowly or becomes rewetted can have considerable microbial growth on it causing nutrient losses. Mechanical handling of dry hay also leads to considerable losses (Savoie, et al., 1982). Raising the baling moisture decreases leaching, microbial and mechanical losses in the field; however, hay baled too wet will heat severely, causing of nutrients. Spontaneous combustion can occur with

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[1] All moisture levels in this thesis are percent wet basis unless otherwise noted.

even more severe consequences (Hoffman and Bradshaw, 1937; Bohstedt, 1944).

In an effort to increase the safe baling moisture limit, preservatives such as salts, organic acids, anhydrous ammonia, urea, and bacterial inoculants have been used with varying degrees of success.

3.2 DRY MATTER LOSS

Baled alfalfa decreases in weight during storage due to loss of moisture and loss of dry matter. Baled hay approaches 14 - 15 % moisture in storage. When it reaches moisture equilibrium with the environmental conditions, no more moisture weight loss will occur. Dry matter loss in storage is due to continued respiration and microbial activity which may occur when there is sufficient moisture in the environment for this activity.

Most researchers report a correlation between baling moisture and dry matter loss (Rotz, et al., 1984; Nelson 1966; Nelson, 1968; Nelson, 1972; Jorgensen, et al.,1978); however, no models for predicting dry matter loss have been proposed. Martin (1980) suggested hay may lose 5 - 10 % dry matter if baled with less than 20% moisture. Jorgensen, et al., (1978) reported that nontreated hay baled at over 20% moisture resulted in 14% dry matter loss.

Dry matter loss of baled alfalfa hay is a function of several factors such as baling moisture, maturity, bale density, and the type of storage facility. For a fixed storage condition, the primary factor was moisture and the secondary factor was maturity. Density was reported to have no effect on dry matter loss (Nelson, 1966, 1968).

Storage loss data for non-chemically treated baled hay from several researchers (Martin, 1980; Koegel, et al., 1983; Shepherd, et al., 1966) was compiled, and a simple linear regression model was developed from the data. Although conditions were not identical for each researcher, a good correlation between baling moisture and dry matter loss was obtained. Fifteen (15) data points were used (3 remote points were removed) to develop this relationship:

$$DML = 77.0*MI - 10.71 \quad (3.1)$$

$(r^2 = 0.93 \quad \text{std. error} = 1.3)$

Where:

DML = dry matter loss (% of initial)
MI = moisture content at baling (decimal wet basis)

Because data from several tests were combined to get this relationship, it should not be taken as an accurate indicator, rather as a motivator for study in this area.

Waldo and Jorgensen (1981) suggested the following rule of thumb: 1% loss in dry matter for each 1% decrease in moisture content during storage. Since hay usually approaches 15% moisture in storage, this rule indicates a 5% loss at 20% moisture, 10% loss at 25% moisture, etc. Equation (3.1) indicates nearly a 0.8% loss in dry matter for each percentage point increase in baling moisture. With the reasonable assumption that all hay approaches the same moisture level in storage, equation (3.1) is in reasonable agreement with that rule of thumb.

3.3 QUALITY CHANGES

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 with up to 40% moisture. However, other research indicates that as hay is baled with moisture levels exceeding 20% and normal density levels, the heat and mold occurring do affect nutrient retention (Miller et al., 1967). Several researchers have reported significant quality changes during storage as baling moisture was increased (Jorgensen, et al., 1978; Miller, et al., 1967; Nehrir, et al., 1978; Nelson, 1966; Nelson, 1968).

Miller, et al. (1967) listed the effects of baling moisture on several quality properties of baled alfalfa hay. This information is summarized in Table 3.1

Nelson (1968) published numerous graphs of the effect of moisture level on nutrient retention in non-chemically treated high density bales. Retention of all chemical constituents measured was significantly decreased by increasing baling moisture. Maturity significantly affected retention of carbohydrates, organic matter, crude fat, and dry matter. Maturity did not significantly affect retention of crude protein, crude fiber, or nitrogen free extract.

Table 3.1 Effect of moisture content of baled alfalfa hay on quality parameters (Miller et al., 1980.).

Property	Effect of Increased Bale Moisture
Crude Protein Content	no effect
Ash Content	increased
Cell Wall Constituents	increased
Cellulose Content	increased
Acid Detergent Fiber Content	increased
Lignin Content	increased
Water Soluble Carbohydrates	no effect
Dry Matter Digestibility	decreased
Crude Protein Digestibility	decreased
Digestibility of Water Soluble Carbohydrates	decreased
Gross Energy	decreased

3.4 THERMAL PROPERTIES

The thermal properties of baled hay are difficult to estimate because hay is porous, contains varying amounts of water and may be composed of different types of hay materials. Some work has been done to estimate thermal conductivity, specific heat and thermal diffusivity for alfalfa silage (Jiang, et al., 1985), but this material is very different from baled hay. Jiang, et al., (1985) evaluated thermal properties for chopped hay varying in moisture content from 50 to 80% and varying in wet density from 400 to 800 Kg/m^3. Hay stored in the form of bales is not chopped, and varies from approximately 12 to 27% in moisture and 100 to 250 Kg/m^3 in wet density[2]. Although the results found by Jiang, et al. (1985) should not be used in baled hay applications they, are listed here for comparison. Specific heat, thermal conductivity, and thermal diffusivity equations obtained through regression procedures for haylage type materials were as follows:

$$C_a = 2.2573 - 0.003237*D_w + 0.0001197*D_w*m \qquad (3.2)$$

$$A = 0.1829 - 9.22(10)^{-5}*D_w + 0.6(10)^{-7}*D_w^2 - 1.08(10)^{-6}*m^2 \qquad (3.3)$$

$$K = 0.2236 - 0.0003074*D_w - 0.001061*m + 0.00000816*D_w*m \qquad (3.4)$$

Where:

m = moisture (% wet basis)
A = thermal diffusivity (m^2/sec)
C_a = specific heat (KJ/Kg°C)
K = thermal conductivity (W/m°C)
D_w = wet density (Kg/m^3)

Mohsenin (1980) discusses procedures for evaluating thermal properties and gives results from research done to evaluate thermal properties. A relationship for thermal diffusivity of baled hay as a function of density was presented by Ott and Horbut (1964). For a given moisture level of 8.2%, the following relationship was found:

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2 Wet density refers to density as is (wet basis). Dry density (or dry matter density) refers to the equivalent density if the material contained 0% moisture.

$$Y = 0.0233 - 0.000804 * X \qquad (3.5)$$

Where:

Y = thermal diffusivity (Ft^2/h)
X = density (lb/ft^3)

Siebel (1892) proposed two equations for specific heat for food materials, one based on temperatures above freezing, the other based on temperatures below freezing. For temperatures above freezing, the specific heat equation was:

$$C_b = 0.008*m + 0.20 \qquad (3.6)$$

Where:

C_b = specific heat (Btu/lb^oF)
0.2 = assumed specific heat of the dry solid

For materials with high moisture contents, Siebel's equation gives a reasonable estimate of specific heat; however, for low moisture material, more error occurs. Bern (1964) conducted experiments to evaluate the specific heat of ground alfalfa. As shown in Mohsenin (1980), Bern's results indicated a good correlation between moisture content and specific heat. No equation is given, but estimating from a given figure (pg. 49, Mohsenin, 1980), equation (3.7) is approximately true for moisture levels between 4 and 20 percent wet basis.

$$C_c = 0.22 + 0.0142 * m \qquad (3.7)$$

Where:

C_c = specific heat (cal/gm^oC)

Conversion of Siebel's equation (3.6) into the units of equation (3.7) results in equation (3.8):

$$C_c = 0.199 + 0.00797 * m \qquad (3.8)$$

Equations (3.7) and (3.8) are in reasonable agreement for predicting specific heat. In order to use either equation, we need to consider the hay/air mixture to be one solid with water as the second material. This is a reasonable assumption since the baled hay is dense enough that natural convective currents within the stored material would be minimal. For forced ventilation drying models, this assumption would need to be modified.

Thermal conductivity of baled alfalfa has not been measured. A form of predicting thermal conductivity of wet solids is given by Andersen (1950). It is similar to Siebel's equation for specific heat:

$$K = M*K_{water} + (1-M)*K_{solid} \qquad (3.9)$$

Where:

K = thermal conductivity of the wet hay/air mixture (W/m^oC)
K_{water} = thermal conductivity of water (W/m^oC)
K_{solid} = thermal conductivity of the dry hay/air mixture (W/m^oC)

In order to use this equation for baled hay, the thermal conductivity of dry baled hay is needed. Again, as in the method for predicting specific heat, the hay/air mixture should be considered as one solid with water as the second material.

3.5 HEATING IN STORAGE

As moisture content increases when hay is baled, heat development during storage increases. Temperatures of stored hay up to 50°C (122°F) do not significantly affect quality, but as the bale temperatures exceed 60°C (140°F), feed value is decreased. Rotz, et al. (1983) reported the following linear regression equation for maximum bale temperature (°C) versus baling moisture for untreated hay in small (10 bale) stacks:

$$T_{max} = 4.38 + (1.38 * m) \qquad (3.10)$$

$$(r = 0.90)$$

Equation (3.10) implies that in order to keep temperatures below 50°C (122°F), the hay must be less than 33% in moisture. This figure should be used very conservatively because it pertains to a very small stack. Large stacks are known to attain temperatures above 50°C (122°F) even though baling moisture may be less than 33%. Heat generated within the hay cannot be dissipated as rapidly from large stacks as from smaller stacks. Also, Jorgensen et, al. (1978) suggested not baling at over 30% moisture because of shrink and stack movement. With few exceptions, (e.g. Koegel, et al., 1983) baled alfalfa over the 30% moisture level cannot be preserved adequately with any form of preservation.

Several researchers have published time/temperature curves for hay bales in storage (Nelson, 1968; Nelson 1966; Weeks, et al., 1975; Hathaway, et al., 1984; Koegel, et al., 1983; Miller, et al., 1967). Nelson (1966 ,1968, 1972) gives curves for degree days of heating for varying moisture and density levels. This indicates a total amount of heating, but does not indicate when or how fast this internal heat generation occurs. Models predicting heat generation rates for baled alfalfa hay in storage have not yet been presented.

3.6 PRESERVATIVES

Preservatives are used in baled alfalfa to raise the upper limit on the safe baling moisture. Effects of preservatives are various, but the ideal preservative should:

1. Increase nutrient retention and perhaps add nutrients.
2. Increase dry matter retention.
3. Suppress temperature rises.
4. Inhibit mold development.
5. Be cost effective.
6. Be safe and easy to apply.

3.6.1 ORGANIC ACIDS

Organic acids, primarily propionic[3] or its salts, are the most commonly used preservatives in baled alfalfa. The effect of propionic acid on dry matter retention has been debated. Several researchers have reported improved dry matter retention in acid treated hays (Davies and Warboys, 1978; Jorgensen, et al., 1978; Nehrir, et al., 1978). Johnson and McCormick (1976) treated hay with Hay Savor[4] (a commercial product) which did not affect dry matter retention. Davies and Warboys (1978) reported that acid treated hay dried to a lower level during storage. The advantage of this may be a longer allowable storage period.

Jorgensen, et al. (1978) reported effective hay preservation with moisture levels to 30-35% with treatments of 1) propionic acid, 2) Chemstor (a commercial product), and 3) propionic acid plus formaldehyde. Acid treatments reduced heating and molding; however, in vitro dry matter digestibility was lower for treated hay than for the dry control hay. Davies and Warboys (1978) reported improved nutrient retention due to treatment in only one experiment. Nutrient retention was not improved by Hay Savor (Johnson and McCormick, 1976).

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3 Also known as propanoic acid (CH_3CH_2COOH).

4 Trade names are used solely to provide specific information. Mention of a trade name does not constitute a warranty of the product by Michigan State University, nor an endorsement of the product to the exclusion of other products not mentioned.

Suggested application rates for propionic acid are: 1, 1.5, and 2% of hay mass for 20-25, 25-30, and 30-35% moisture hay, respectively (Schaeffer and Martin, 1979).

3.6.2 ANHYDROUS AMMONIA

Anhydrous ammonia (NH_3) can be successfully used as a preservative for high moisture hay. Applied at a rate of 1% of dry matter, anhydrous ammonia preserved alfalfa hay with up to 33% moisture (Knapp, et al., 1975). Koegel, et al. (1983) successfully preserved alfalfa at the 50% moisture level with ammonia treatment at a rate of 2.5% (wet basis).

Most often, application of anhydrous ammonia is done in storage. Bales are first wrapped in plastic, then anhydrous ammonia is slowly released into the hay. Some investigations have been performed by injecting ammonia into the bales prior to placement into storage (Koegel, et al., 1983; Rotz, et al., 1984); however, wrapping the hay is still necessary to prevent the ammonia from escaping (Hathaway, et al., 1984).

Treating wet alfalfa with anhydrous ammonia significantly reduces dry matter loss (Knapp, et al., 1975). Rotz, et al. (1984) reported dry matter loss for ammoniated (22.1-32.1% moisture) hay to be similar to that of non-chemically treated dry (12.5-15.8% moisture) hay.

Quality improvement of alfalfa hay treated with anhydrous ammonia is mainly an increase of crude protein content. This is due to the presence of additional nitrogen which can be utilized by rumen bacteria. Ammonia treatment also inhibits mold development, (Koegel, et al., 1983; Knapp, et al., 1975) improves physical appearance, (Rotz, et al., 1984; Koegel., et al., 1983) and suppresses temperature rises after the initial heat of solution (Hathaway, et al., 1984; Rotz, et al., 1984; Knapp, et al., 1975).

For a preservative to be effective, it must stop respiration (i.e., CO_2 production) in the harvested forage. Hathaway, et al. (1984) reported that 1840 ppm of ammonia gas is necessary to inhibit carbon dioxide production.

Anhydrous ammonia is not widely used as a hay preservative. The primary reason is safety. Anhydrous ammonia can cause severe burns and can be extremely irritable to the eyes and skin. Handling of anhydrous ammonia and application equipment must be done with proper precautions and safety equipment such as gas masks and rubber gloves. However, treated hay may be safely handled after the ammonia has been absorbed by the moisture in the hay (Rotz et al, 1984). Ammonia treatment can also cause toxicity to animals when application rates exceed 3.0% of dry matter (Rotz et al., 1984).

3.6.3 OTHER PRESERVATIVES

In addition to organic acids and anhydrous ammonia, salts, bacterial inoculants, and urea have been the subject of some research as preservatives for baled hay.

Using sodium chloride as a preservative is not a new idea. It was used before the invention of the refrigerator to cure meats. However, as a hay preservative, it has not been as successful. To be effective, salt must be applied at a rate of 1 to 2% of the hay weight. At this rate, feeding problems have been experienced (Moser 1980).

Bacterial inoculants have been tried as preservatives for baled hay, but not successfully (Rotz, et al., 1983). Inoculants are added to ensiled products to improve fermentation and promote fermentation at lower temperatures. Usually inoculants help the lactic acid producing bacteria gain control of the preservation over the spoilage bacteria. Since fermentation in baled alfalfa is not desirable, inoculants which aid fermentation will probably not act as preservatives in baled alfalfa. Also, effectiveness of inoculants is dependent upon the moisture of the forage. Moisture levels in baled alfalfa are usually too low for effective growth of inoculating bacteria and preservation by inoculants.

Urea, like bacterial inoculants, is better suited to silages. It has been used for several years in corn silage in order to increase the non-protein nitrogen (NPN) level. It has been applied in granular form to baled hay, however, preservation was not improved (Rotz, et al., 1983).

4. EXPERIMENTAL PROCEDURE

4.1 HARVESTING OF HAY TREATMENTS

Three experiments were conducted; one each from first, second and third cutting alfalfa. In each experiment, the same basic procedure was followed.

The standing crop was cut when between 10 and 50% bloom. It was mown with a 2.7 m wide mower-conditioner with a cutterbar and intermeshing rubber rolls for conditioning. The alfalfa was laid into a full width swath approximately 2.1 m wide for faster and more uniform drying. Sufficient hay was mown for 7 to 8 bales per treatment. Hay was then tedded and raked at different moisture levels so drying would take place at different rates. The moisture levels at which the swaths were handled depended upon the weather conditions. Some treatments required no tedding, while others were tedded then raked twice. Handling the swath in this manner allowed for baling of different moisture levels at nearly the same time.

The target treatments were all possible combinations of 6 moisture levels and 2 density levels. Target moisture levels were 45, 40, 35, 30, 25, 20, and 15% wet basis. Density levels were set somewhat arbitrarily, one being high density (>10Kg/m^3), the other being low density (<8 Kg/m^3). Two treatments per experiment were treated with propionic acid (Table 4.1). In test three, the six driest target treatments were not baled due to lack of hay and poor weather. The term treatment is used in this context as "different bale conditions", not as "chemical treatment" or "handling practice".

Table 4.1 Target treatments of moisture content and density desired for the hay storage experiments.

Moisture (% w.b.)	Low Density (<8 kg/m^3)	High Density (>10 kg/m^3)
40	X	X
35	X	X
30	X	X
30[a]		X
25	X	X
25[b]		X
20	X	X
15	X	X

[a] With propionic acid applied at 2.0 % of hay mass.
[b] With propionic acid applied at 1.5 % of hay mass.

When the windrow moisture level was near a target moisture level, 7 or 8 bales of the treatment were baled with a Sperry New Holland model 310 baler. No special features or changes were used to form the bales; however, the baler did have a hydraulic bale tensioner rather than the standard spring type. Bale density was varied by adjusting the pressure to the hydraulic tensioner on the baler. Low density was achieved by setting the gage pressure to 0 kPa (0 psig), and high density was achieved by setting the gage pressure to approximately 1750 kPa (250 psig). For each treatment, five bales of consistent moisture and density were placed into storage.

4.2 INITIAL SAMPLING

After the bales were formed, core samples of 2.5 cm by approximately 40 cm were taken with a Penn State core sampler. For determination of moisture content, three bales per treatment were cored at least once each from an end. These samples were dried in a 60°C oven for 2 to 3 days. The moisture levels given by these three samples were averaged to give a moisture level for the treatment. The mean size of the samples used for initial moisture content determination was 38.8 grams.

After the core sampling was completed, each bale was weighed, and the length measured for determination of density and dry matter content. Dry matter was computed using the average moisture level for the treatment and individual bale weights. Density was computed using the bale weight and dimensions given by the bale length and cross sectional area of the baler chamber (36.8 cm x 45.7 cm).

4.3 STORAGE

Following all initial sampling, the treatment sets of five bales each were placed side by side in stacks for storage inside a barn. No forced ventilation or auxiliary heating was used. Stacking procedure is illustrated in Figure 4.1. Styrofoam sheets of 5.0 cm thickness with a thermal conductivity (k) value of $0.0267 W/m^{o}K$ were placed between each treatment to help isolate the treatments.

During the first 30 days of storage, ambient and bale temperatures were recorded every 6 hours by a Campbell, model CR5, data logger. Three thermocouples were placed per treatment in select bales. They were located one each in the three center bales of each treatment stack. The thermocouples were placed in the bored hole created by the core sample taken for moisture content determination (see section 4.2). The approximate thermocouple position within the bale was 30 cm from the end, on the centerline of the bale. The bored holes were plugged after the thermocouples were in place.

4.4 FINAL SAMPLING

Because temperatures stabilized after approximately 30 days in storage, any change or loss occurring in stored hay was assumed to occur during the first 30 days. Final sampling was done 60 days after baling to assure that all treatments had stabilized.

Final sampling was performed in the same manner as the initial sampling; however, bale lengths were not measured. The mean size of the samples used for final (60 day) moisture content determination was 40.0 grams.

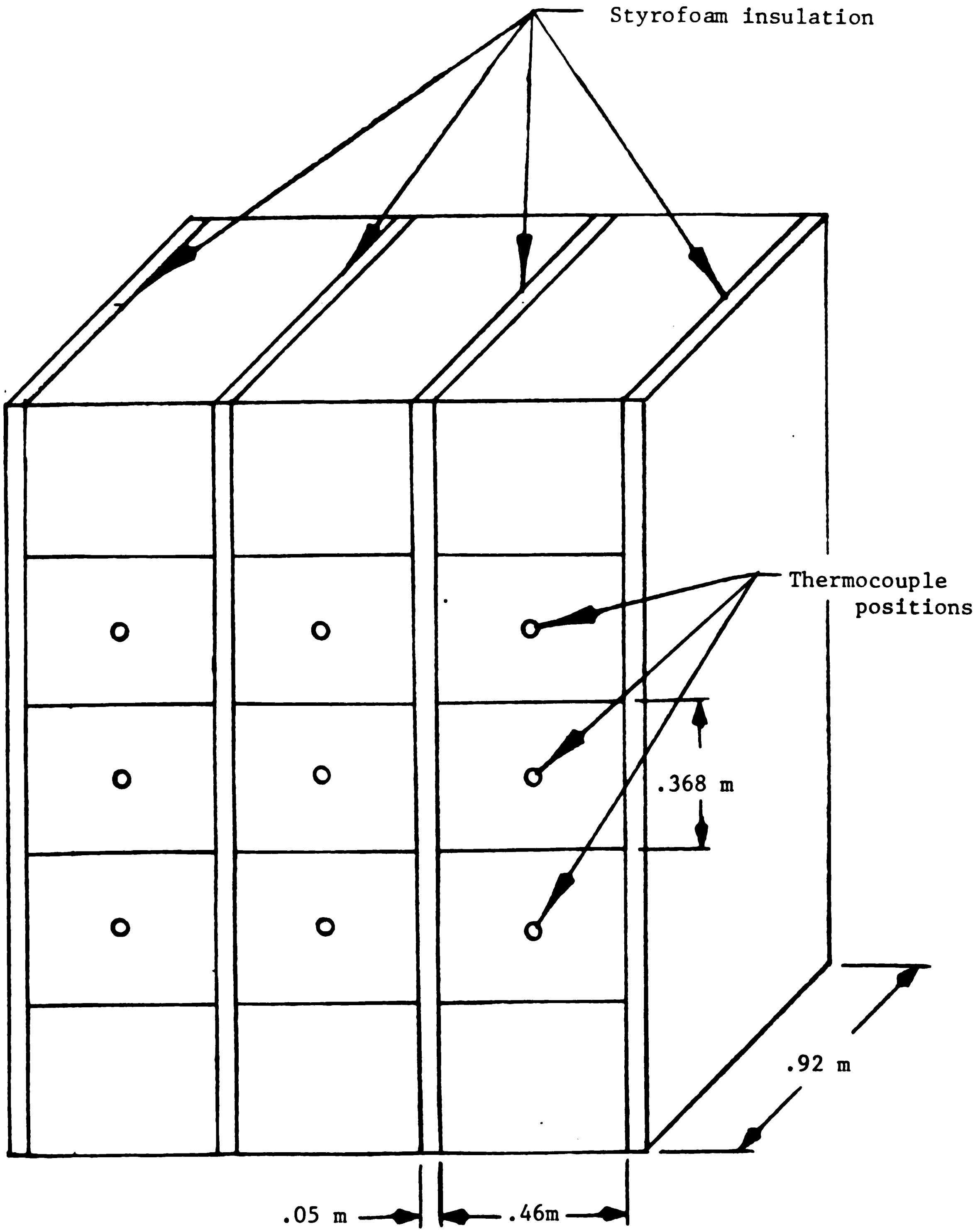

Figure 4.1 Stacking procedure for storage experiments.

5. DATA ANALYSIS

All data was separated into two sets for analysis. One set included data collected from all treatments described in Table 4.1. The other set was only data collected from treatments which were not treated with propionic acid. Temperatures and dry matter loss values for these treatments were generally more consistent because effects of the acid treatment were removed.

5.1 DRY MATTER LOSS

Moisture contents and bale weights measured initially and after 60 days in storage were used to estimate the total amount of dry matter in each bale at these times. Dry matter loss was the difference between initial and 60 day dry matter values, expressed as a percent of the initial dry matter:

$$DML = 100*(IDM - FDM)/IDM \tag{5.1}$$

Where:

DML = dry matter loss as a percent of initial dry matter
IDM = initial dry matter
FDM = final dry matter

Dry matter loss values were calculated for each bale. The dry matter loss value for a treatment was the mean of the five dry matter loss values from the five bales of a treatment. For each of the three experiments, one-way analysis of variance was used to determine treatment effects on dry matter loss. Duncan's Multiple Range Test was used to determine which treatments within an experiment had significantly different dry matter loss values.

Results from all experiments were combined so a two-way analysis of variance could be used for dry matter loss analysis. Moisture contents were divided into 5 ranges and density was divided into 3 ranges. Dry matter loss was broken down by moisture and density to determine significance of each.

Data collected from the three experiments was also combined for a correlation analysis. Pearson's product moment correlation coefficients were used to determine which variables were correlated. Correlations between dry matter loss and other storage variables such as baling moisture and density were observed.

5.2 TEMPERATURE

Individual bale temperature data was collected once every six hours (see section 4.3). These temperatures were averaged over a 24 hour period to give a mean daily temperature. Since there were three thermocouples per treatment, there were three mean daily temperature values per treatment.

The mean daily temperatures were compared over the first 30 days of storage to find the maximum temperature reached by each treatment stack. Thirty days of temperature data with

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three thermocouples per treatment gave 90 mean daily temperature values per treatment. These mean daily temperatures were first analyzed using two-way analysis of variance and a breakdown of temperature by treatment by repetition to assure that there were no noticeable errors in temperature measurements within a treatment. The 90 mean daily temperature values for each treatment were averaged to give a mean treatment temperature for the first 30 days in storage. One-way analysis of variance was used to determine treatment effects on mean temperature. Duncan's Multiple Range Test was used to determine treatments within an experiment which had significantly different mean temperatures.

Days for which the hay stack temperature exceeded 35°C were also summed to calculate the heating in the form of degree days.

Correlations of temperatures and heating to moisture, density, and dry matter loss were determined with the data collected from the three experiments combined. Pearson's product moment correlation coefficients were used to determine which variables were significantly correlated.

6. EXPERIMENTAL RESULTS

6.1 TREATMENTS

As discussed in Experimental Procedure (section 4.1), several target treatments were desired. When the treatments were harvested, not all target treatments were represented. Yet, others were obtained more than once per experiment. Table 6.1 summarizes the actual treatments obtained. Treatments in experiment 1 were as close to the target treatments as could be expected. The second experiment did not have the higher moisture levels and experiment 3 did not have the lower moisture levels; however, a good range of moisture and density levels was achieved by the combination of the three experiments.

6.2 DRY MATTER LOSS

Dry matter loss measurements in the three experiments ranged from 0.6 to 19.5%. Experiments 1 and 2 had a wider range of moisture levels (Table 6.1) and thus, had a wider range of resulting dry matter loss values. Dry matter loss values from experiment 2 were lower because the target treatments with higher moisture levels were not reached. The mean standard deviation of the dry matter loss values for a given treatment within experiments 1, 2, and 3 were 6.3, 3.8, and 4.3 respectively. This indicates that dry matter loss

Table 6.1 Treatments with varying moisture contents and densities obtained in three experiments.

Experiment Number	Treatment Label	Moisture (% w.b.)	Density (Kg/m^3)
1	101	11.5	111
1	102	14.6	175
1	103	16.9	75
1	104	14.3	172
1	105	24.2	91
1	106	25.4	236
1	107	27.7	106
1	108	31.0	268
1	109	30.4	128
1	110	35.2	289
1	111	48.0	189
1	112	43.0	302
1	113	19.3[a]	233
1	114	27.2[b]	252
2	201	16.7	74
2	202	16.2	199
2	203	18.3	87
2	204	16.9	175
2	205	18.3	100
2	206	17.3	191
2	207	18.4	100
2	208	20.8	202
2	209	24.5	111
2	210	27.0	225
2	211	32.7	130
2	212	32.2	273
2	213	21.7[a]	228
2	214	30.2[c]	250
3	301	23.4	101
3	302	24.0	252
3	303	30.5	175
3	304	30.5	295
3	305	34.7	172
3	306	36.9	287
3	307	35.0	164
3	308	36.2	300
3	309	29.0[b]	244

[a] Treated with 1.2 % (of wet weight) propionic acid.
[b] Treated with 1.6 % (of wet weight) propionic acid.
[c] Treated with 1.7 % (of wet weight) propionic acid.

was measured more accurately in the latter two experiments.

Hay which has been baled wet provides a damp environment which is conducive to microbial growth. The microbes consume hay dry matter and in turn, generate heat from their activity. Respiration rate is also higher in wet hay than in dry hay. Since both microbial activity and respiration are causes of dry matter disappearance, a positive correlation between moisture and dry matter loss was expected.

Results of one-way analyses of variance performed separately for each of the three experiments indicated that treatment effects of moisture and density on dry matter loss were very significant. Two-way analysis of variance was used to determine if moisture, density, or an interaction between moisture and density were significant factors. Moisture levels were divided into 5 ranges and density levels were divided into 3 ranges. Significance levels of moisture, density and interaction of the two were $p=.01$, $p=.10$, and $p=.02$ respectively. From these results, moisture is the most important factor affecting dry matter loss.

The dry matter loss values corresponding to given bale conditions are included in Tables 6.2, 6.3, and 6.4 along with statistical evaluations. Dry matter loss was consistently increased with an increase in baling moisture.

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Table 6.2 Dry matter loss, maximum and mean temperatures, and heating for five-bale stacks of alfalfa baled at varying moisture and density levels (Experiment 1).

Baling Moisture (% w.b.)	Baled Density (Kg/cu m)	Dry Matter Loss[1] (%)	Temperatures[2] Maximum (°C)	Mean (°C)	Heating[3] Deg.Days
11.5	111	2.1[ab]	25.9	18.6[a]	0
14.6	175	2.8[ab]	24.0	18.4[a]	0
16.9	75	0.6[a]	24.6	17.9[a]	0
14.3	172	2.2[ab]	25.8	18.2[a]	0
24.2	91	4.7[abc]	24.7	18.0[a]	0
25.4	236	9.9[d]	47.6	32.8	117
27.7	106	5.8[bc]	28.6	21.0[bc]	0
31.0	268	8.6[c]	42.2	28.6[d]	81
30.4	128	5.7[bc]	34.8	22.8[c]	17
35.2	289	12.1[d]	57.9	36.8	247
48.0	189	17.8[e]	59.7	30.6	169
43.0	302	19.5[e]	62.4	41.5	354
19.3[4]	233	3.3[ab]	26.2	18.0[ab]	0
27.2[5]	252	11.3[d]	36.5	29.5[d]	18

1 Dry matter loss during a 60 day storage period.
2 Maximum temperature during the first 30 days of storage. Mean temperature over the first 30 days of storage.
3 Degree days that temperature measurements exceeded 35°C.
4 Propionic acid applied at a rate of 1.2% (wet basis).
5 Propionic acid applied at a rate of 1.6% (wet basis).
abcde Superscript letters indicate values which were not significantly different by Duncan's Multiple Range Test ($p < 0.05$).

Table 6.3 Dry matter loss, maximum and mean temperatures, and heating for five-bale stacks of alfalfa baled at varying moisture and density levels (Experiment 2).

Baling Moisture (% w.b.)	Baled Density (Kg/cu m)	Dry Matter Loss[1] (%)	Temperatures[2] Maximum (°C)	Mean (°C)	Heating[3] Deg.Days
16.7	74	4.1^{ab}	26.9	21.2^{a}	0
16.2	199	1.8^{a}	33.1	22.6^{a}	0
18.3	87	5.0^{abcd}	27.1	21.8^{a}	0
16.9	175	3.5^{a}	37.0	25.6^{b}	14
18.3	100	2.4^{a}	26.3	21.9^{a}	0
17.3	191	3.8^{ab}	39.9	27.6^{d}	17
18.4	100	3.4^{a}	26.0	21.4^{a}	0
20.8	202	4.5^{abc}	46.1	30.2	45
24.5	111	5.8^{abcd}	37.9	24.4^{bc}	4
27.0	225	8.9^{cd}	46.5	34.6	103
32.7	130	9.2^{d}	43.8	27.6^{d}	32
32.2	273	9.0^{cd}	55.2	41.4	252
21.7[4]	228	5.9^{abcd}	36.7	28.3^{d}	4
30.2[5]	250	8.3^{bcd}	34.0	26.5^{cd}	1

[1] Dry matter loss during a 60 day storage period.
[2] Maximum temperature during the first 30 days of storage.
Mean temperature over the first 30 days of storage.
[3] Degree days that temperature measurements exceeded 35°C.
[4] Propionic acid applied at a rate of 1.2% (wet basis).
[5] Propionic acid applied at a rate of 1.7% (wet basis).
[abcd] Superscript letters indicate values which were not significantly different by Duncan's Multiple Range Test ($p < 0.05$).

Table 6.4 Dry matter loss, maximum and mean temperatures, and heating for five-bale stacks of alfalfa baled at varying moisture and density levels (Experiment 3).

Baling Moisture (% w.b.)	Baled Density (Kg/cu m)	Dry Matter Loss[1] (%)	Temperatures[2] Maximum (°C)	Mean (°C)	Heating[3] Deg.Days
23.4	101	2.8[a]	24.3	11.6	0
24.0	252	4.4[ab]	39.1	26.8[c]	22
30.5	175	12.0[de]	42.9	25.8[c]	49
30.5	295	9.6[cd]	46.5	32.0	112
34.7	172	10.0[cd]	44.4	24.9[bc]	62
36.9	287	9.4[cd]	50.2	40.0[d]	218
35.0	164	11.4[d]	46.4	23.2[ab]	62
36.2	300	15.0[e]	52.7	41.3[d]	250
29.0[4]	244	6.9[bc]	32.1	21.3[a]	0

[1] Dry matter loss during a 60 day storage period.
[2] Maximum temperature during the first 30 days of storage. Mean temperature over the first 30 days of storage.
[3] Degree days that temperature measurements exceeded 35°C.
[4] Propionic acid applied at a rate of 1.6% (wet basis).
[abcde] Superscript letters indicate values which were not significantly different by Duncan's Multiple Range Test ($p < 0.05$).

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Even with baling moisture as low as 11.5%, there were no treatments which had a dry matter loss value of zero (0.0). This indicates either: 1) the baling moisture must be lower than approximately 11.5% to eliminate dry matter loss, or 2) that there exists a threshold dry matter loss which occurs regardless of bale conditions.

Tables 6.5 and 6.6 include Pearson product moment correlation coefficients for dry matter loss related to other storage parameters. Table 6.5 contains the coefficients obtained using only data collected from non-chemically treated stacks while results found in Table 6.6 were obtained using all treatments. When data from stacks treated with propionic acid were included, significance levels of correlations were not affected but coefficients were lowered.

Two-way analysis of variance suggested that dry matter loss was related to moisture. Correlation analysis also indicated a relationship, as there was a very significant positive correlation between dry matter loss and baling moisture (r=.92)[1]. A scatter plot of the data illustrates the relationship (Figure 6.1).

Effects of propionic acid treatment are difficult to determine from the data. Treatments with propionic acid applied did not have the same moisture and density levels as nontreated stacks. Comparisons of acid treated stacks to non-chemically treated stacks with somewhat similar moisture

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[1] Correlation coefficients mentioned in the text are for non-chemically treated hay (Table 6.5).

Table 6.5 Pearson product moment correlation coefficients for several storage parameters of non-chemically treated alfalfa hay.[a]

	Moisture Content	Density	Max. Temp.	Mean Temp.	Degree Days
Density	.54				
Max. Temp.	.83	.80			
Mean Temp.	.65	.85	.90		
Degree Days	.75	.80	.87	.90	
D. M. Loss	.92	.61	.87	.73	.82

[a] All coefficients were significant at the p=.01 level.

Table 6.6 Pearson product moment correlation coefficients for several storage parameters of untreated and acid treated alfalfa hay.[a]

	Moisture Content	Density	Max. Temp.	Mean Temp.	Degree Days
Density	.51				
Max. Temp.	.81	.69			
Mean Temp.	.64	.76	.89		
Degree Days	.72	.67	.86	.87	
D. M. Loss	.91	.58	.85	.73	.78

[a] All coefficients were significant at the p=.01 level.

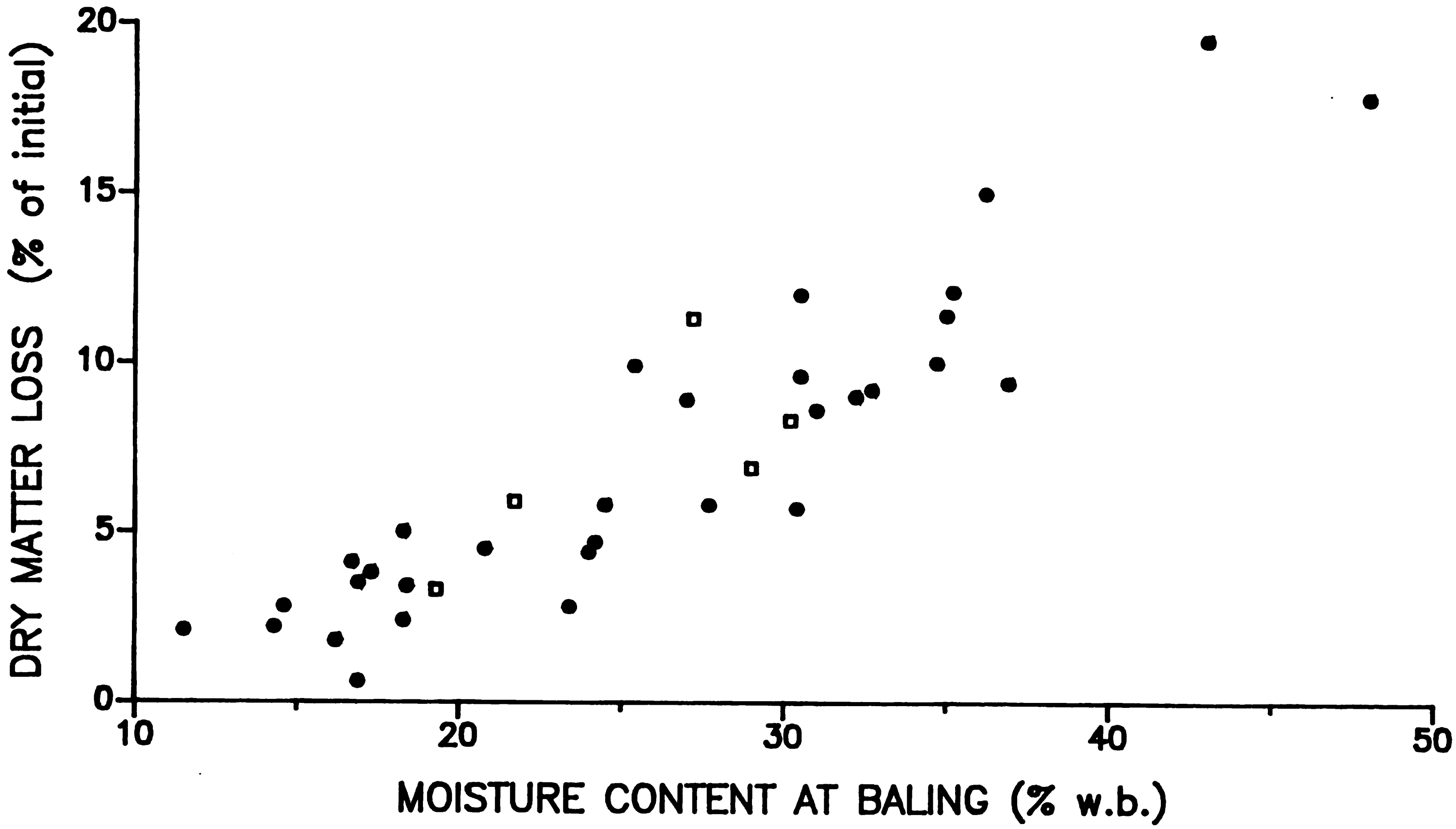

Figure 6.1 Dry matter loss vs baling moisture for small stacks of rectangularly baled alfalfa hay (Experimental data).

and density levels show that propionic acid did not reduce dry matter loss, as compared to no chemical treatment in experiments 1 and 2. Experiment 3 gave some indication that dry matter loss is reduced when propionic acid is applied.

6.3 TEMPERATURE

Wet hay continues to respire more than dry hay. It also provides a more favorable environment for microbial growth. With these sources of heat, temperatures should increase more in wet hay than in dry hay. The experimental results support this hypothesis.

The maximum temperatures of each treatment stack during the first 30 days in storage are included in Tables 6.2, 6.3, and 6.4. Correlation analysis (Tables 6.5 and 6.6) indicated that both moisture ($r=.83$) and density ($r=.80$) are significantly correlated to maximum temperature. Positive correlations show that increased moisture and/or density levels were related to an increase in maximum temperature ($p=.05$). Figure 6.2 shows the relationship between moisture and maximum temperature.

Results of the one-way analyses of variance performed separately for each of the three experiments indicated that treatment effects on mean temperature during the first 30 days in storage were significant (Tables 6.2, 6.3, and 6.4). Therefore, moisture and/or density levels significantly affect storage temperatures ($p=.05$).

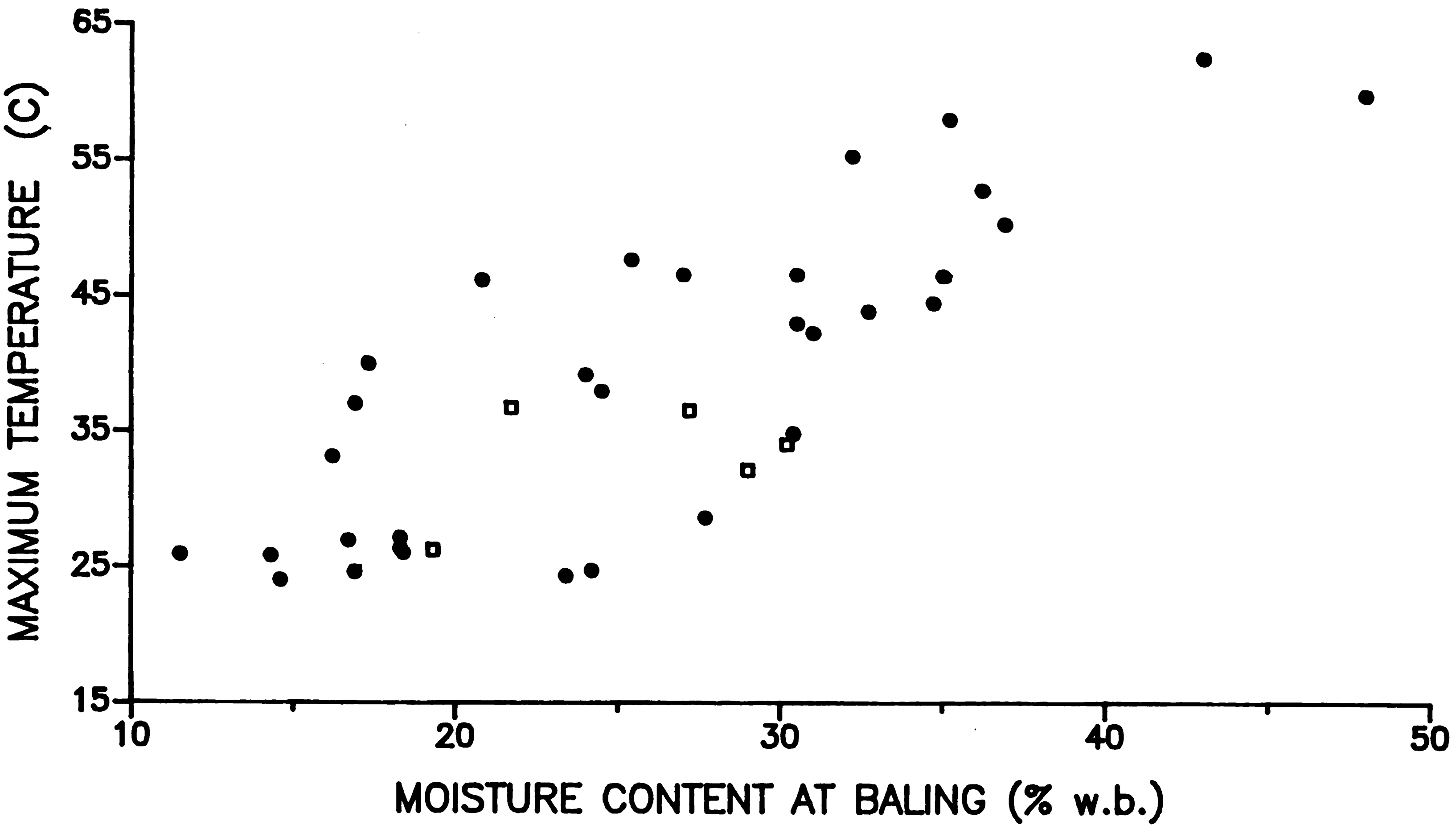

Figure 6.2 Maximum storage temperature vs baling moisture for small stacks of rectangularly baled alfalfa hay (Experimental data).

Comparisons of treatments with similar densities and different moisture levels indicate that an increase in moisture content at the time of baling will increase mean temperatures in storage (r=.65). Increased mean temperature with increased moisture is in agreement with the concept that respiration rate is higher in wetter hay and microbial activity increases with increasing moisture. Figure 6.3 illustrates the relationship between baling moisture and mean temperature.

Similarly, comparisons of treatments with similar moistures and different density levels indicate that increased bale density led to increased storage temperatures (r=.85). This may be explained by the amount of heat generated. Heat generation should be expressible in terms of heat generated per unit mass (eg. W/Kg). Denser hay would then generate more heat per unit volume. Each stack was of approximately the same volume; therefore, if more heat were generated in a dense stack, temperatures may be higher. This would depend upon the specific heat of the material.

Days for which the bale temperatures exceeded 35^{o}C were summed to compute heating, in the form of degree days, for each treatment. These values are also included in Tables 6.2, 6.3, and 6.4. Correlation coefficients (Tables 6.5 and 6.6) indicate that an increase in baling moisture and/or density is related to an increase in heating. This was expected since both mean and maximum temperatures were correlated in a similar manner. Figure 6.4 illustrates

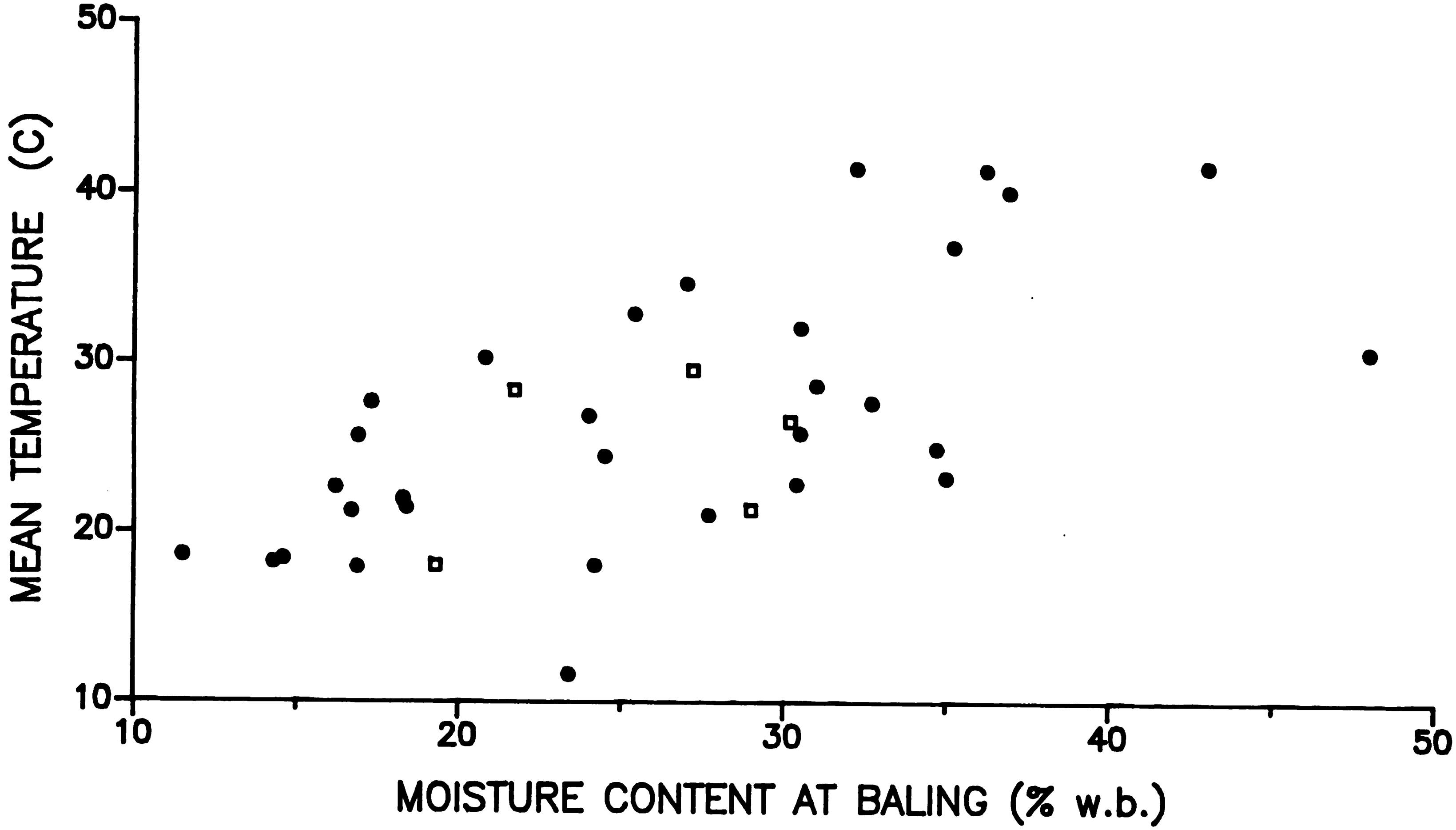

Figure 6.3 Mean storage temperature vs baling moisture for small stacks of rectangularly baled alfalfa hay (Experimental data).

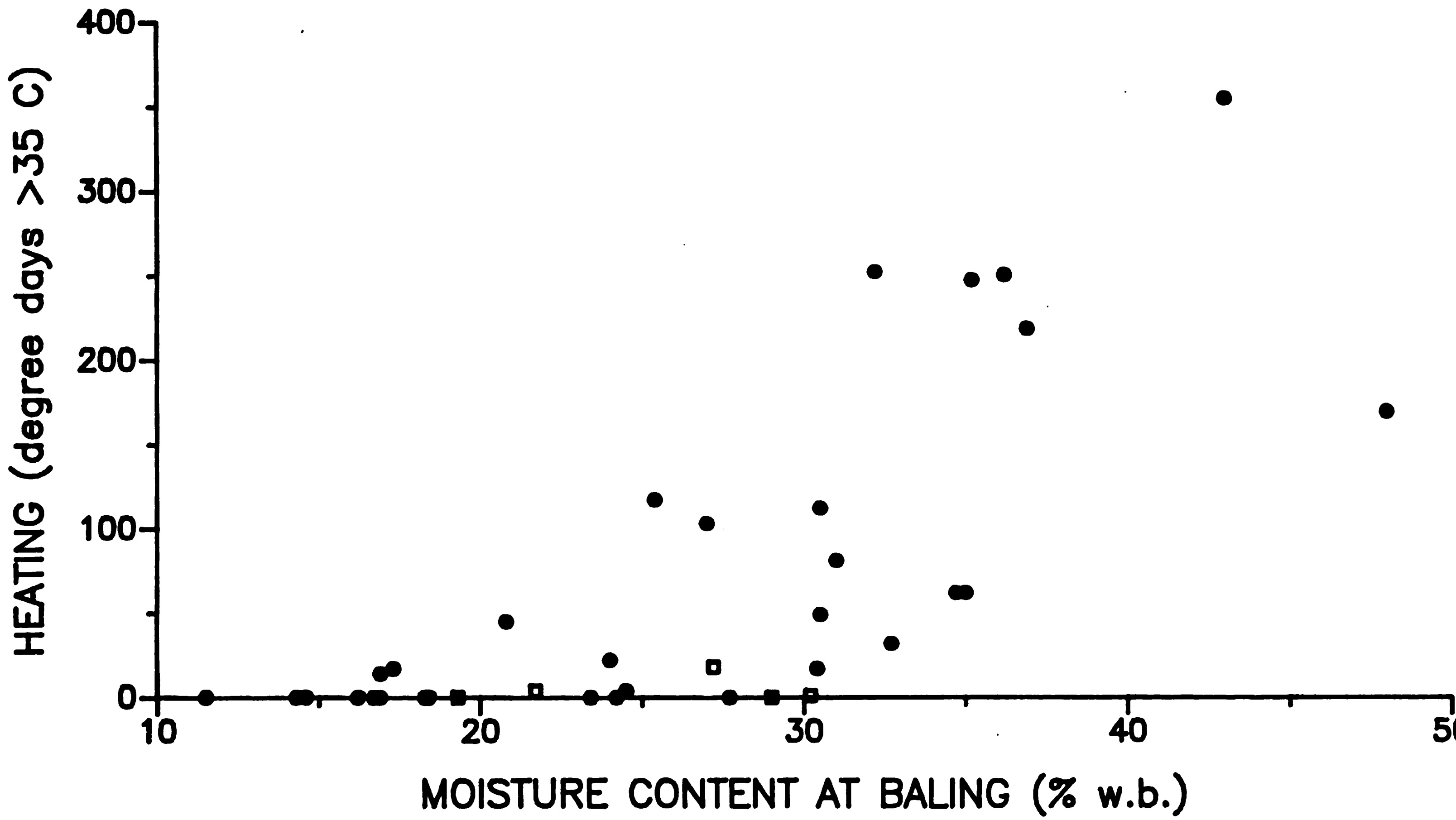

Figure 6.4 Heating in degree days vs baling moisture for small stacks of rectangularly baled alfalfa hay.

the relationship between baling moisture and heating in degree days.

Hay dry matter serves as fuel for respiration and microbial activity. As more of the fuel is "burned", more heat is generated. This heating causes temperatures to rise. It is no surprise that the data indicated positive correlations between dry matter loss and temperatures reached during storage (Tables 6.5 and 6.6). Maximum temperature had a higher correlation (r=.87) to dry matter loss than mean temperature (r=.73) or heating in degree days (r=.82).

Results from all three experiments show that propionic acid treatment reduces maximum and 30 day mean temperatures in storage as compared to no chemical treatment. Heating in degree days is also reduced through propionic acid treatment. Lower temperatures may be the result of decreased microbial activity. Since temperatures in acid treated hay were lower, it would seem to follow that dry matter loss would be reduced for acid treated hay (since it is correlated to temperatures and heating); however, this was not evident from the data collected in this study.

7. MODEL DEVELOPMENT

7.1 DRY MATTER LOSS

One objective of this research was to develop a functional relationship which predicts dry matter loss from baling moisture content and initial density. Since moisture and density influenced dry matter loss (section 6.2), a model of the relationship between dry matter loss and baling moisture and density was feasible.

Data from Tables 6.2, 6.3, and 6.4, for which no propionic acid treatment was involved, were used to develop the dry matter loss models.

Dry matter density can be expressed in terms of moisture level and wet density:

$$D_d = D_w - (M * D_w) \tag{7.1}$$

$$= (1 - M) * D_w \tag{7.2}$$

Where:

D_d = dry matter density
D_w = wet density (as is)
M = moisture content (decimal wet basis)

With this relationship, dry matter density was used as an independent variable in some instances, rather than an interaction term of moisture times wet density ($M*D_w$). Stepwise multiple regression was used to develop the model.

Results from the analysis of variance indicated that moisture content was the most important variable affecting dry matter loss. A scatter plot of the dry matter loss as related to baling moisture content (Figure 6.1) indicates a linear relationship between dry matter loss and moisture level. Therefore, a linear regression analysis was used. Adding density, either wet or dry, as an independent variable to the equation already including moisture, did not improve the accuracy of the prediction (p=.05). The model which best predicted dry matter loss as a function of baling moisture was (Figure 7.1):

$$DML = -5.4 + (48.0 * MI) \tag{7.3}$$

$(r^2 = .85 \quad \text{std. error} = 1.9)$

Where:

DML = dry matter loss (% of initial)
MI = moisture content at baling (decimal wet basis)

The r^2 value of 0.85 indicates that 85% of the variance in the dry matter loss data was explained by baling moisture. Dry matter loss increased approximately 0.5% for each percentage point increase in baling moisture (p=.05). This is approximately half the dry matter loss as predicted by a rule of thumb given by Waldo and Jorgensen (1981). The discrepancy may be due to the crudeness of a rule of thumb, and the differences between large and small hay stacks.

Correlation coefficients shown in Tables 6.5 and 6.6 indicate that dry matter loss was also related to temperatures during storage (p=.05). Regression models were used to establish relationships between dry matter loss and storage temperatures.

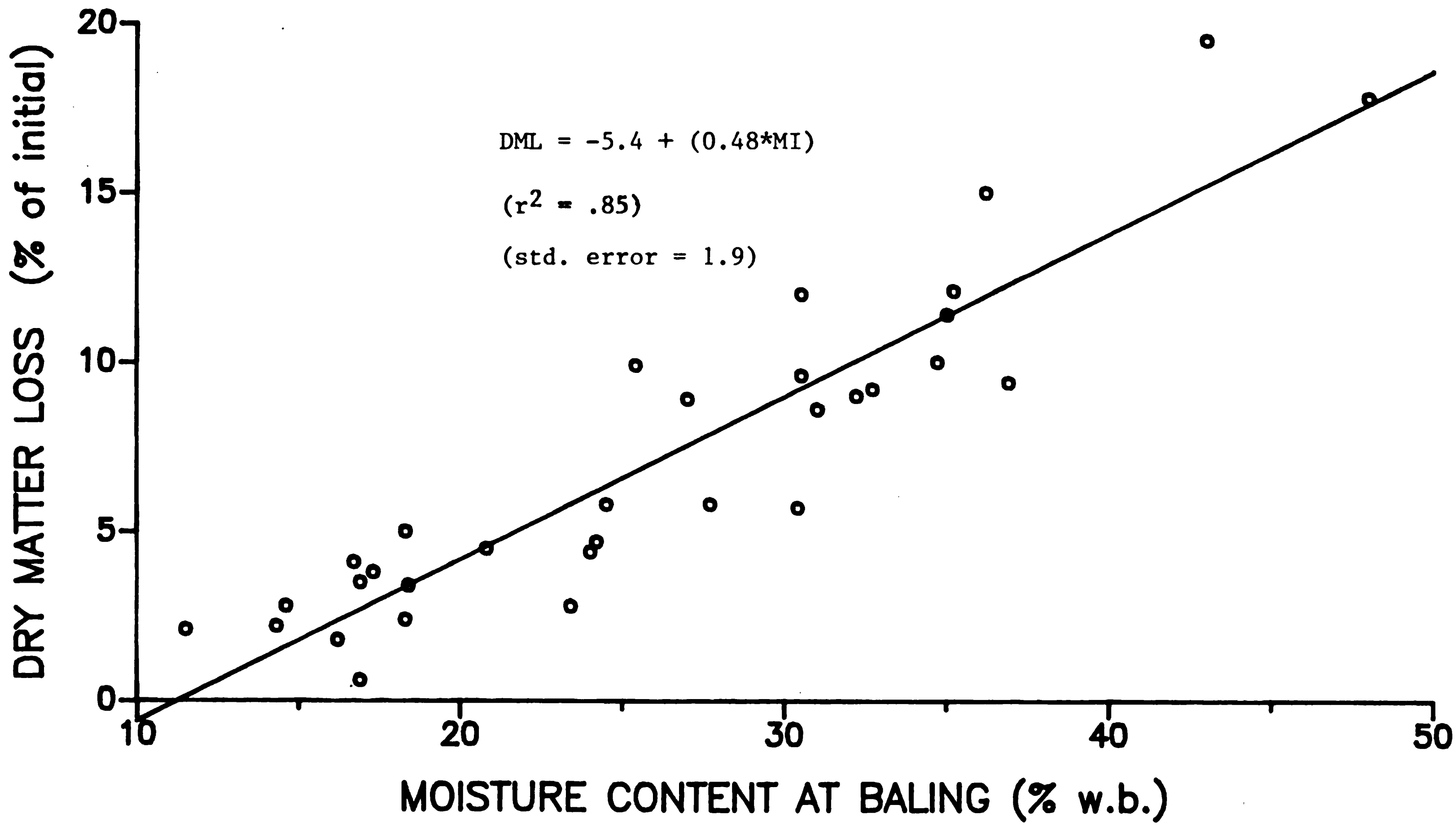

Figure 7.1 Dry matter loss as a function of baling moisture for rectangularly baled alfalfa hay.

A scatter plot of dry matter loss versus maximum temperature (Figure 7.2) indicates a non-linear relationship. Stepwise regression analysis was used to develop a quadratic relationship between dry matter loss and maximum temperature. The best fit curve for the data was:

$$DML = 0.00432 * (T_{max})^2 \qquad (7.4)$$

$(r^2 = .81 \qquad \text{std. error} = 2.1)$

Where:

T_{max} = maximum temperature reached in storage (C)

A constant term did not improve the regression equation (p=.05).

A plot of the mean temperature versus dry matter loss indicates a linear relationship (Figure 7.3). Simple linear regression was used to find the best fit model:

$$DML = -4.7 + (0.45 * T_{mean}) \qquad (7.5)$$

$(r^2 = .57 \qquad \text{std. error} = 3.3)$

Where:

T_{mean} = mean temperature over the first 30 days in storage (C)

The previous models were developed from data collected from those treatments without propionic acid application. In an effort to determine if propionic acid decreases dry matter loss, further regression analysis was performed. For this model, all data in tables 6.2, 6.3, and 6.4 were used. Stepwise regression was used with dry matter loss as the dependent variable. Independent variables were moisture, wet

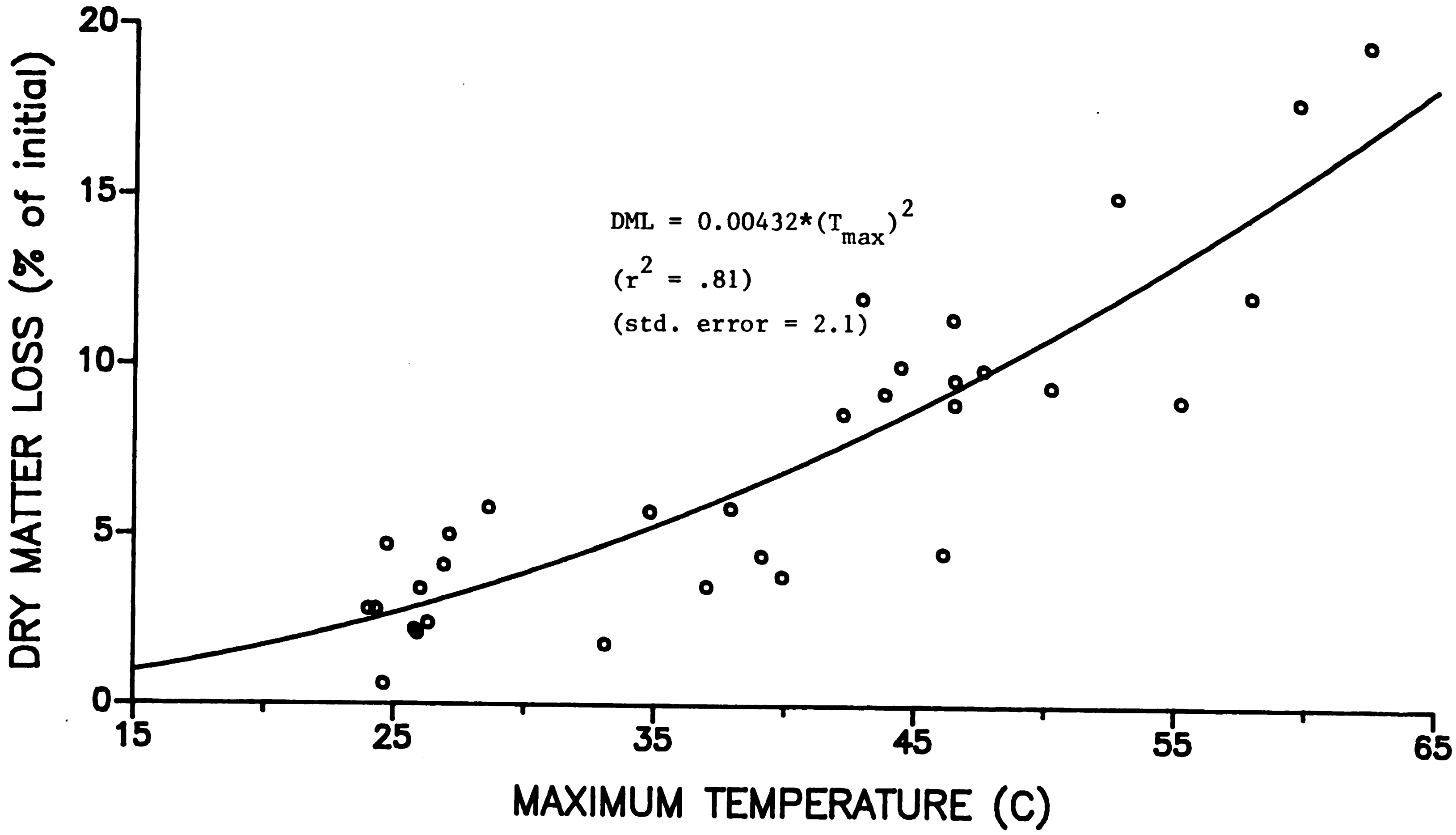

Figure 7.2 Dry matter loss as a function of maximum storage temperature of rectangularly baled alfalfa hay.

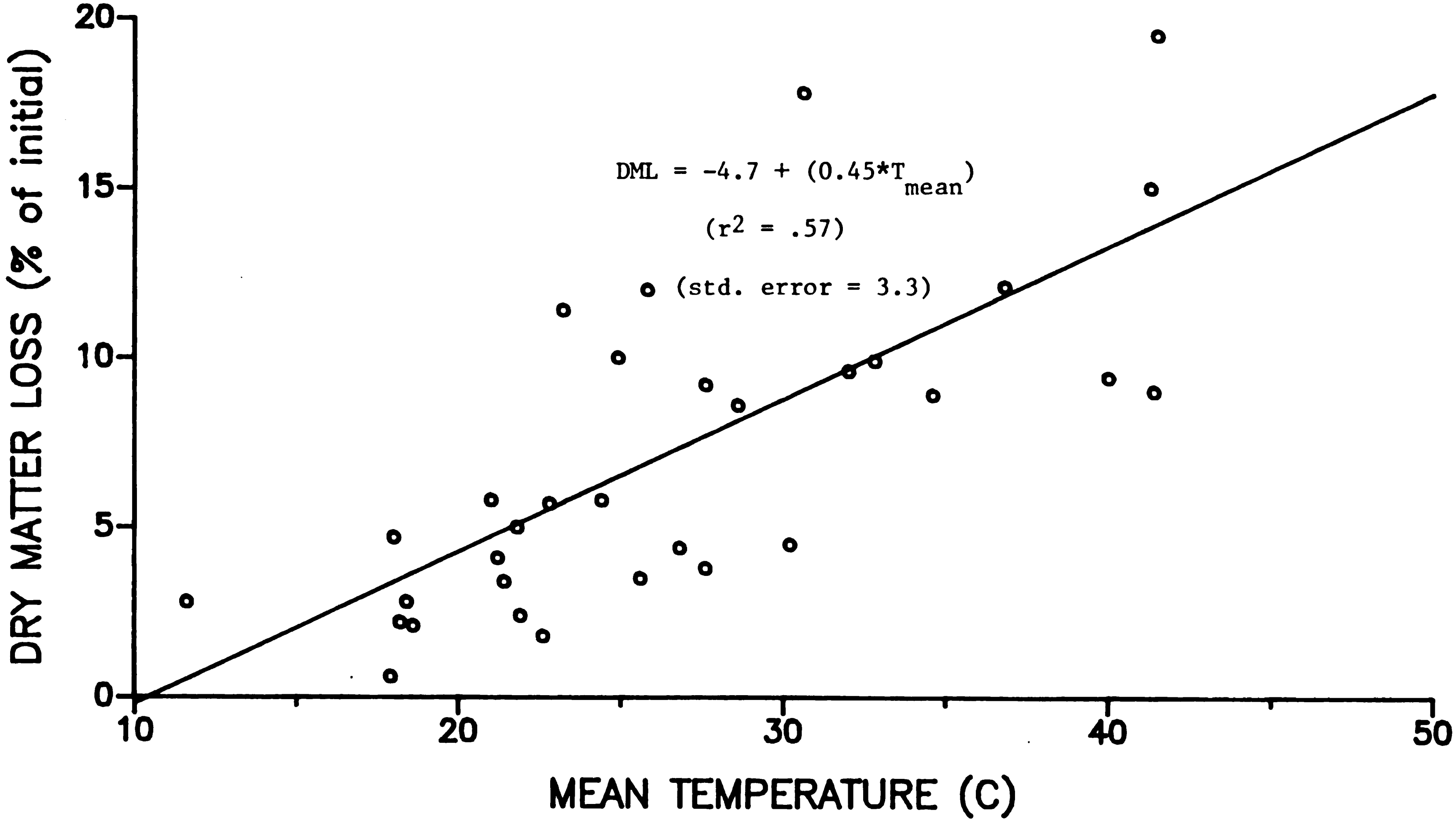

Figure 7.3 Dry matter loss as a function of mean storage temperature of rectangularly baled alfalfa hay.

density, dry density, and propionic acid application rate. Again as in the previous model (7.1), density did not affect dry matter loss (p=.05). Propionic acid application rate did affect dry matter loss (p=.07). Dry matter loss as a function of baling moisture and propionic acid application rate was:

$$DML = -5.4 + (49.0 * MI) - (1.32 * P) \quad (7.6)$$

(R^2 = .62 std. error = 3.3)

Where:

P = propionic acid application rate (% of wet weight)

From this model propionic acid treatment reduced dry matter loss (p=.07). The loss reduction (retention gain) is approximately 1.3% for each percentage point increase in application rate. Equation (7.6) is in excellent agreement with equation (7.3) when a propionic acid rate of zero (0.0) is used. Data used for the model (7.6) was collected from treatments having application rates of propionic acid ranging from 0 to 1.7%. Use of this model beyond this range of application rates may not yield correct conclusions.

The regression models involving dry matter loss are summarized in Table 7.1.

Table 7.1 Regression models of dry matter loss, maximum temperature, mean temperature, and heating in degree days as functions of baling moisture and initial density.[a]

	Equation	r^2/R^2	std. error
	Propionic treatments deleted:		
1.	$DML = -5.4 + (48.0 * MI)$	.85	1.91
2.	$DML = 0.00432 * (T_{max})^2$	.81	2.14
3.	$DML = -4.7 + (0.45 * T_{mean})$	.57	3.28
4.	$T_{max} = 6.2 + (72.0 * MI) + (0.078 * DI_w)$	.89	4.60
5.	$T_{mean} = 7.4 + (24.0 * MI) + (0.073 * DI_w)$	.83	3.80
6.	$DD = -186 + (490 * MI) + (0.71 * DI_w)$	.78	47.00
	Propionic treatments included:		
7.	$DML = -5.4 + (49.0 * MI) - (1.32 * P)$	.62	3.29
8.	$T_{max} = 7.4 + (78.0 * MI) + (0.062 * DI_w) - (4.1 * P)$	.84	5.00
9.	$T_{mean} = 7.5 + (28.0 * MI) + (0.062 * DI_w) - (2.7 * P)$	.78	3.90
10.	$DD = -175 + (520 * MI) + (0.59 * DI_w) - (50.0 * P)$	.74	47.00

DI_w = wet density at baling (Kg/m^3.)
MI = moisture content at baling (decimal wet basis)
T_{max} = maximum temperature reached in storage (C)
T_{mean} = mean temperature during the first 30 days in storage (C)
P = application rate of propionic acid (% of wet weight)
DD = degree days above 35°C
DML = dry matter loss (% of initial)

[a] All coefficients are over the p=.05 significance level with an exception in equation 7 {1.32 (*P) is at p=0.07 level}.

7.2 TEMPERATURE

Stepwise regression procedures were used to develop relationships between moisture, wet density, dry density, and propionic acid application rate to mean temperature, maximum temperature, and heating in degree days. The temperature and heating models presented here are applicable only to small stacks (approximately 5 bales). Two sets of data were used. The first included only data from Tables 6.2, 6.3, and 6.4 corresponding to treatments without propionic acid applied. With a significance level of 0.05 required for a variable to be included in the equation, the following relationships were obtained:

$$T_{max} = 6.2 + (72.0 * MI) + (0.078 * DI_w) \quad (7.7)$$

$$(R^2 = .89 \quad \text{std. error} = 4.60)$$

$$T_{mean} = 7.4 + (24.0 * MI) + (0.073 * DI_w) \quad (7.8)$$

$$(R^2 = .83 \quad \text{std. error} = 3.80)$$

$$DD = -186 + (490 * MI) + (0.71 * DI_w) \quad (7.9)$$

$$(R^2 = .78 \quad \text{std. error} = 47.0)$$

All data from Tables 6.2, 6.3, and 6.4 was used in the second analysis to determine the effects of propionic acid treatment on storage temperatures. Again with a significance level of 0.05 required for a variable to be used in the equation, the following relationships were obtained:

$$T_{max} = 7.4 + (78.0 * MI) + (0.062 * DI_w) - (4.1 * P) \quad (7.10)$$

$$(R^2 = .84 \quad \text{std. error} = 5.00)$$

$$T_{mean} = 7.5 + (28.0 * MI) + (0.062 * DI_w) - (2.7 * P) \quad (7.11)$$

$$(R^2 = .78 \quad \text{std. error} = 3.90)$$

$$DD = -175 + (520 * MI) + (0.59 * DI_w) - (50.0 * P) \quad (7.12)$$

$$(R^2 = .74 \quad \text{std. error} = 47.0)$$

These three equations are in reasonable agreement with (7.7), (7.8), and (7.9) when a propionic acid rate of zero (0.0) is used. Mean temperature, maximum temperature, and heating in degree days during storage are each decreased significantly by the application of propionic acid and increased significantly by increases in moisture and/or density levels. The regression models involving maximum temperature, mean temperature, and heating in degree days are summarized in Table 7.1.

7.3 HEAT GENERATION

As indicated by the temperature models developed in the previous section, wetter alfalfa hay heats more in storage. The models developed so far are for a small stack (5 bales). To make the results useful for simulation of a larger stack, a different modeling approach is required.

In order to predict temperatures in a large stack of hay, the heating rate of the stored product must be known. Degree days is not an adequate measure of heating since it only quantifies the amount of heat generated above a chosen base temperature and does not indicate the rate of heat generation. A more useful form of energy units would be Watts per kilogram of matter (W/Kg) or Watts per cubic meter (W/m^3). In order to develop some type of model to predict heating in this way, a heat transfer model of the hay stack was developed. Because the heating rate was unknown (most likely being a function of time) and thermal properties would change over time due to the drying process, an analytical solution to the problem was impossible. Therefore, a finite difference model of a hay stack was developed.

7.3.1 FINITE DIFFERENCE MODEL

Figure 7.4 illustrates an individual treatment stack of five bales. Because treatment stacks were placed side by side (Figure 4.1) and insulation was placed between them, there were assumed to be no temperature variations in the z direction (Fig 7.4). By symmetry, the bales were "cut" in half in the x direction and considered to be insulated at the center line. This simple step decreases the number of necessary calculations by 1/2. The bottom of the stack was assumed to be insulated as the hay was placed on a wooden floor. The model is then a two dimensional model with two insulated sides and two convective heat transfer sides (Figure 7.5).

Numerical methods are used quite frequently to solve heat transfer problems. Numerous textbooks and other handbooks discuss the finite difference method. Myers (1971) discusses heat transfer problems in depth.

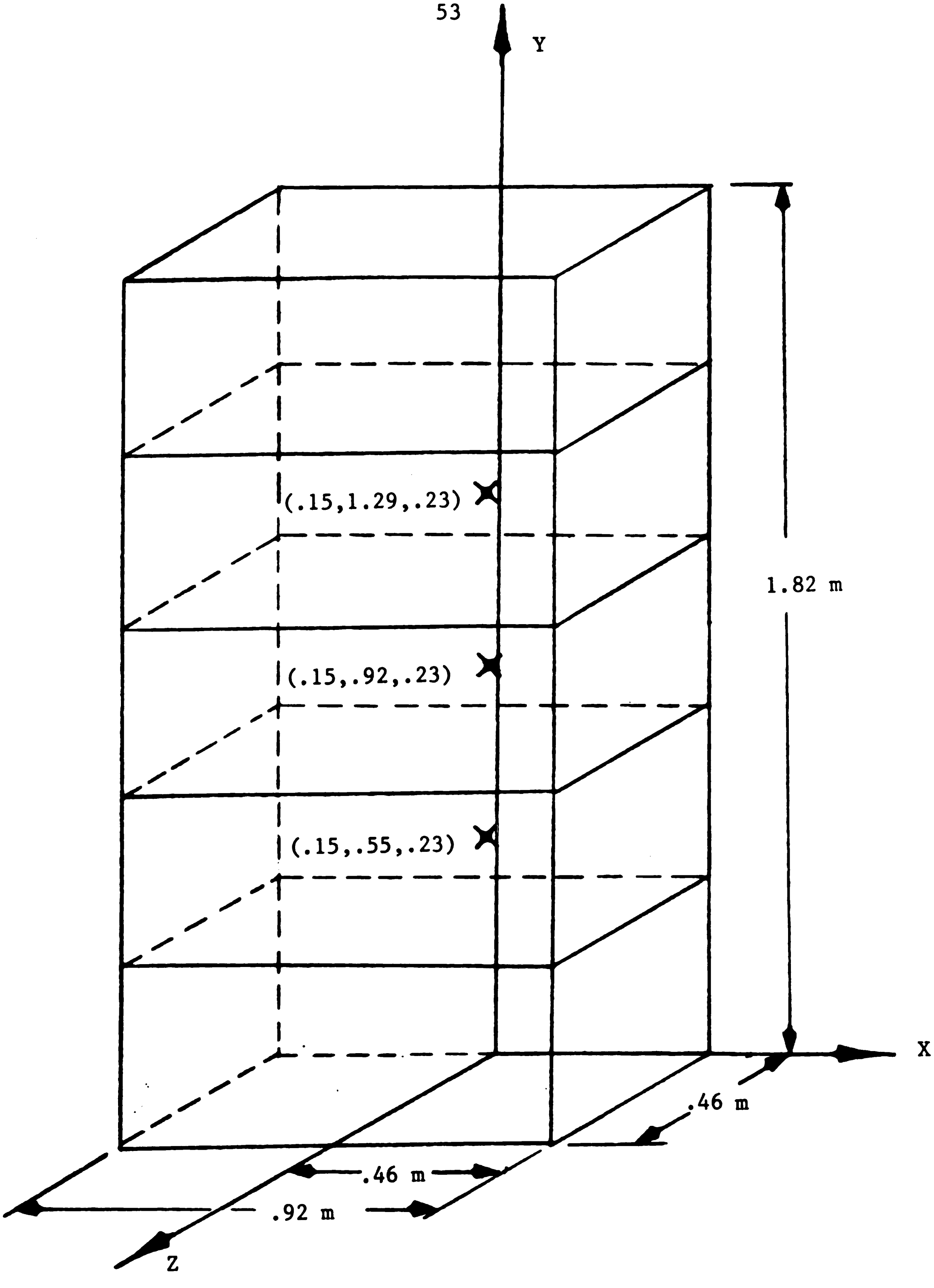

Figure 7.4 Thermocouple positions in a treatment stack of five bales.

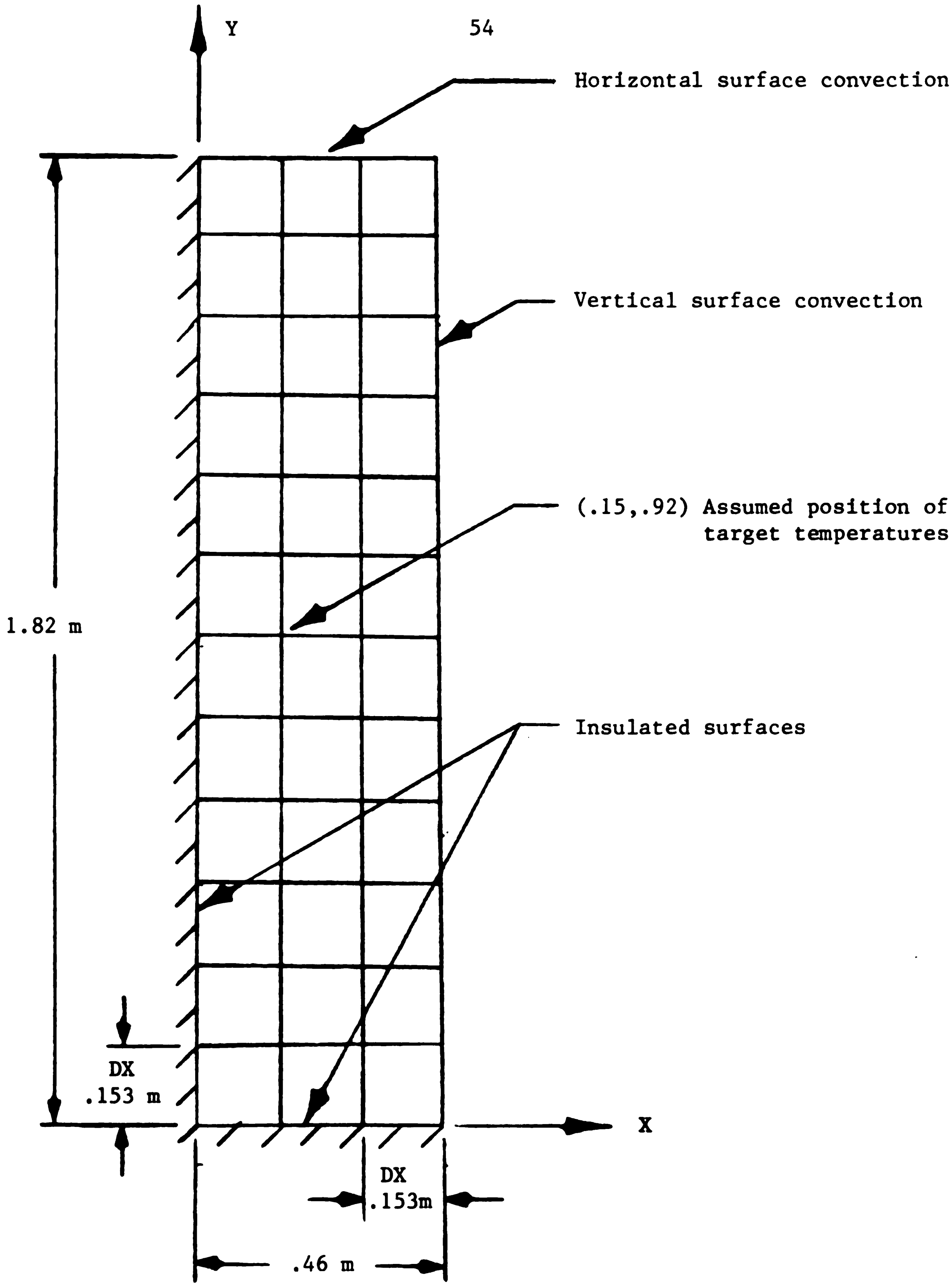

Figure 7.5 Finite difference model of a five bale hay stack.

To simplify the equations, grid length increments on the x and y axes (DX and DY) were taken to be equal. To develop the finite difference equations, the first law of thermodynamics was applied to small control volumes for all positions in the grid. For interior points, the sources of heat were conduction transfer from neighboring control volumes and heat generation. For points along the outside edge, an additional heat source (or sink) was the convection to the ambient air. Applying energy conservation to control volumes for different positions in the stack leads to the following explicit equations:

interior points (x,y) $x \neq 0,w$; $y \neq 0,v$:

$$T_{m,n,p+1} = F*(T_{m+1,n,p} + T_{m-1,n,p} + T_{m,n+1,p} + T_{m,n-1,p} + T_{m,n,p}) + B*G + T_{m,n,p} \quad (7.13)$$

left edge points (0,y) $y \neq 0,v$:

$$T_{m,n,p+1} = 2F*(T_{m+1,n,p} + .5T_{m,n+1,p} + .5T_{m,n-1,p} - 2T_{m,n,p}) + B*G + T_{m,n,p} \quad (7.14)$$

right edge points (w,y) $y \neq 0,v$:

$$T_{m,n,p+1} = 2F*(T_{m-1,n,p} + .5T_{m,n+1,p} + .5T_{m,n-1,p} - 2T_{m,n,p}) + B*G + T_{m,n,p} + (2BH_2/DX)*(T_a - T_{m,n,p}) \quad (7.15)$$

bottom edge points (x,0) $x \neq 0,w$:

$$T_{m,n,p+1} = 2F*(.5T_{m-1,n,p} + .5T_{m+1,n,p} + T_{m,n+1,p} - 2T_{m,n,p}) + B*G + T_{m,n,p} \quad (7.16)$$

top edge points (x,v) x≠0,w :

$$T_{m,n,p+1} = 2F*(.5T_{m-1,n,p} + .5T_{m+1,n,p} + T_{m,n-1,p} - 2T_{m,n,p}) + B*G + T_{m,n,p} + (2BH_1/DX)*(T_a - T_{m,n,p}) \quad (7.17)$$

bottom left corner (0,0) :

$$T_{m,n,p+1} = 2F*(T_{m+1,n,p} + T_{m,n+1,p} - T_{m,n,p}) + B*G + T_{m,n,p} \quad (7.18)$$

top left corner (0,v) :

$$T_{m,n,p+1} = 2F*(T_{m+1,n,p} + T_{m,n-1,p} - 2T_{m,n,p}) + B*G + T_{m,n,p} + (2BH_1/DX)*(T_a - T_{m,n,p}) \quad (7.19)$$

bottom right corner (w,0) :

$$T_{m,n,p+1} = 2F*(T_{m-1,n,p} + T_{m,n+1,p} - 2T_{m,n,p}) + B*G + T_{m,n,p} + (2BH_2/DX)*(T_a - T_{m,n,p}) \quad (7.20)$$

top right corner (w,v) :

$$T_{m,n,p+1} = 2F*(T_{m-1,n,p} + T_{m,n-1,p} - 2T_{m,n,p}) + B*G + T_{m,n,p} + (2A/DX)*(H_1 + H_2)*(T_a - T_{m,n,p}) \quad (7.21)$$

Where:

$B = A*DT/K$
$F = A*DT/(DX)^2$
$T_{i,j,t}$ = temperature (C) at:
x node i
y node j
time = t*DT
H_2 = vertical surface convective heat transfer coefficient ($W/m^2\ ^oC$)
H_1 = horizontal surface convective heat transfer coefficient ($W/m^2\ ^oC$)

G = heat generation rate (W/m^3)
T_a = ambient temperature (C)
DT = time increment (s)
DX = grid length increment (m)
K = thermal conductivity (W/m^oC)
A = thermal diffusivity (m^2/s)

In order for the solution to be stable, the time increment (DT) was limited by the following equation:

$$DT < ((DX^2/A) / (2*(H*DX/K + 1)) \quad (7.22)$$

7.3.2 <u>ESTIMATING THERMAL PROPERTIES</u>

As discussed in the literature review (section 3.5), thermal properties for baled alfalfa hay are not well known. It was desirable to have expressions for thermal conductivity and thermal diffusivity as functions of moisture and density. The thermal properties may also vary with the actual content of the hay (e.g., some grass vs. pure clover or alfalfa) but these differences would likely be much less important than moisture and density. The estimation equations used were taken from references discussed in section 3.5.

Specific heat for alfalfa hay was given by Bern (1964). Changing equation (3.7) to SI units yields:

$$C = 919 + 5933 * M \quad (7.23)$$

Where:

C = specific heat (J/Kg)

According to Andersen (1950), the thermal conductivity of a wet solid is given by:

$$K = M*K_{water} + (1-M)*K_{solid} \quad (3.9)$$

If we consider the hay/air mixture to be the solid and water as the other component, equation (3.9) is adequate once we know the thermal conductivity of the hay/air mixture.

Ott and Horbut gave an equation for thermal diffusivity for hay at 8.2 % moisture. This equation (3.5) converted into SI units is:

$$A_{.082} = 6.01(10)^{-7} + 1.3(10)^{-9}D_w \quad (7.24)$$

Where:

$A_{.082}$ = thermal diffusivity of hay at 8.2% moisture (m^2/s)
D_w = wet density (Kg/m^3)

By definition of thermal diffusivity:

$$A = K/(D*C) \quad (7.25)$$

Where:

A = thermal diffusivity
K = thermal conductivity
C = specific heat
D = density

For the given moisture level of 8.2 % and a given density D_w, then:

$$A_{.082} = K_{.082}/(D_{w,.082}*C_{.082}) \quad (7.26)$$

Where:

subscript .082 refers to the moisture content at which the property is evaluated

If equations (7.23) and (7.24) were exact rather than empirical, substitution of both into equation (7.26) would be exact. Even though they are empirical, some liberty was taken to combine these equations together since this is the best data available. Since the temperature range of concern in this problem is small (10-70^{o}C), the thermal properties would not change considerably with temperature. Substituting equations (3.9), (7.23), and (7.24) into equation (7.26) leads to an expression for K_{solid}:

$$K_{solid} = 9.2(10)^{-4} * D_{w,.082} + 2(10)^{-6} * (D_{w,.082})^2 - .0536 \quad (7.27)$$

Where:

K_{solid} = thermal conductivity of the hay/air solid (W/m^{o}C)
$D_{w,.082}$ = wet density at 8.2% moisture (Kg/m^3)

The known density (D_w) is at a given moisture M. To convert to equivalent density for a moisture level of 8.2% the following relationship can be used:

$$D_{w,.082} = 1.09 * (1-M) * D_w \quad (7.28)$$

These equations, repeated for clarity, along with the measured density, D_w, were used to estimate thermal properties of baled hay:

$$C = 919 + 5933 * M \quad (7.23)$$

$$D_{w,.082} = 1.09 * (1-M) * D_w \quad (7.28)$$

$$K_{solid} = 9.2(10)^{-4} * D_{w,.082} + 2(10)^{-6} * (D_{w,.082})^2 - .0536 \quad (7.27)$$

$$K = M * K_{water} + (1-M) * K_{solid} \quad (3.9)$$

$$A = K/(D_w * C) \quad (7.25)$$

Where:

C = specific heat (J/Kg)

D_w = wet density (Kg/m^3)

M = moisture content (decimal wet basis)

K_{solid} = thermal conductivity of the hay/air solid (W/m^oC)

K_{water} = thermal conductivity of water (W/m^oC)

K = thermal conductivity of wet hay (W/m^oC)

A = thermal diffusivity of wet hay (m^2/s)

To validate the use of the previous five equations for thermal property estimation, known thermal properties of similar substances were compared. The specific heat of hay was assumed to be similar to that of tobacco. Table 7.2 contains the known specific heat of tobacco and estimated specific heat of alfalfa and tobacco. Equation (3.9) predicted the specific heat of tobacco quite well and was thus used to estimate specific heat for alfalfa. Equation (3.2) (Jiang et. al, 1985) did not yield a comparable value for specific heat. This is because the equation is applicable to alfalfa silage which is wetter and more dense than baled alfalfa.

Thermal conductivity of tobacco has not been presented in the literature. It is known for many substances but none quite so similar to baled alfalfa. Granulated cork is used here for comparison (Table 7.3). Estimated thermal conductivity of cork is somewhat higher than the known value. Therefore, the estimated thermal conductivity for alfalfa may be higher than the true value. The thermal conductivity for baled hay as estimated in the model is also higher than that estimated by extrapolating equation (3.4) (Jiang, et. al., 1985).

Table 7.2 Comparison of known and estimated specific heat values of tobacco to estimated specific heat values of hay.

Material	Moisture (% w.b.)	Specific Heat (J/Kg°C)
Tobacco		
(known)[a]	16.6	1431
	28.0	2598
(estimated)[b]	16.6	1904
	28.0	2580
Baled Alfalfa		
(estimated)[b]	20.0	2105
	25.0	2402
(estimated)[c]	20.0	3248
	25.0	3354

[a] Known value for Tobacco taken from Chakrabarti and Johnson, 1972.
[b] Estimated by equation (7.23) as used in the model.
[c] Estimated by equation (3.2) with a density of 176 Kg/m^3 for comparison only.

Table 7.3 Comparison of known and estimated thermal conductivity values of granulated cork to estimated thermal conductivity values of baled hay.

Material	Moisture (% w.b.)	Density (Kg/m^3)	Thermal Conductivity (W/m^oC)
Cork - granulated (known)[a]	?	86	0.05
Cork (estimated)[b]	5.0	86	0.07
Baled alfalfa (estimated)[b]	20.0	176	0.23
	25.0	176	0.24
(estimated)[c]	20.0	176	0.18
	25.0	176	0.18

[a] Known value for granulated cork taken from ASHRAE ,1981.
[b] Estimated by equations (3.9), (7.27), and (7.28) as used in the model.
[c] Estimated by equation (3.4) for comparison only.

7.3.3 ESTIMATING HEAT GENERATION RATES

To estimate thermal properties for the finite difference model developed in section 7.3.1, variations in the moisture and density levels of the hay over time must be known. The data taken provided only initial moisture, 60 day moisture and initial density levels Moisture was assumed to change exponentially over time as illustrated in Figure 7.6. The moisture variation is not known to follow such a curve; however, the hay is drying and should follow a similar

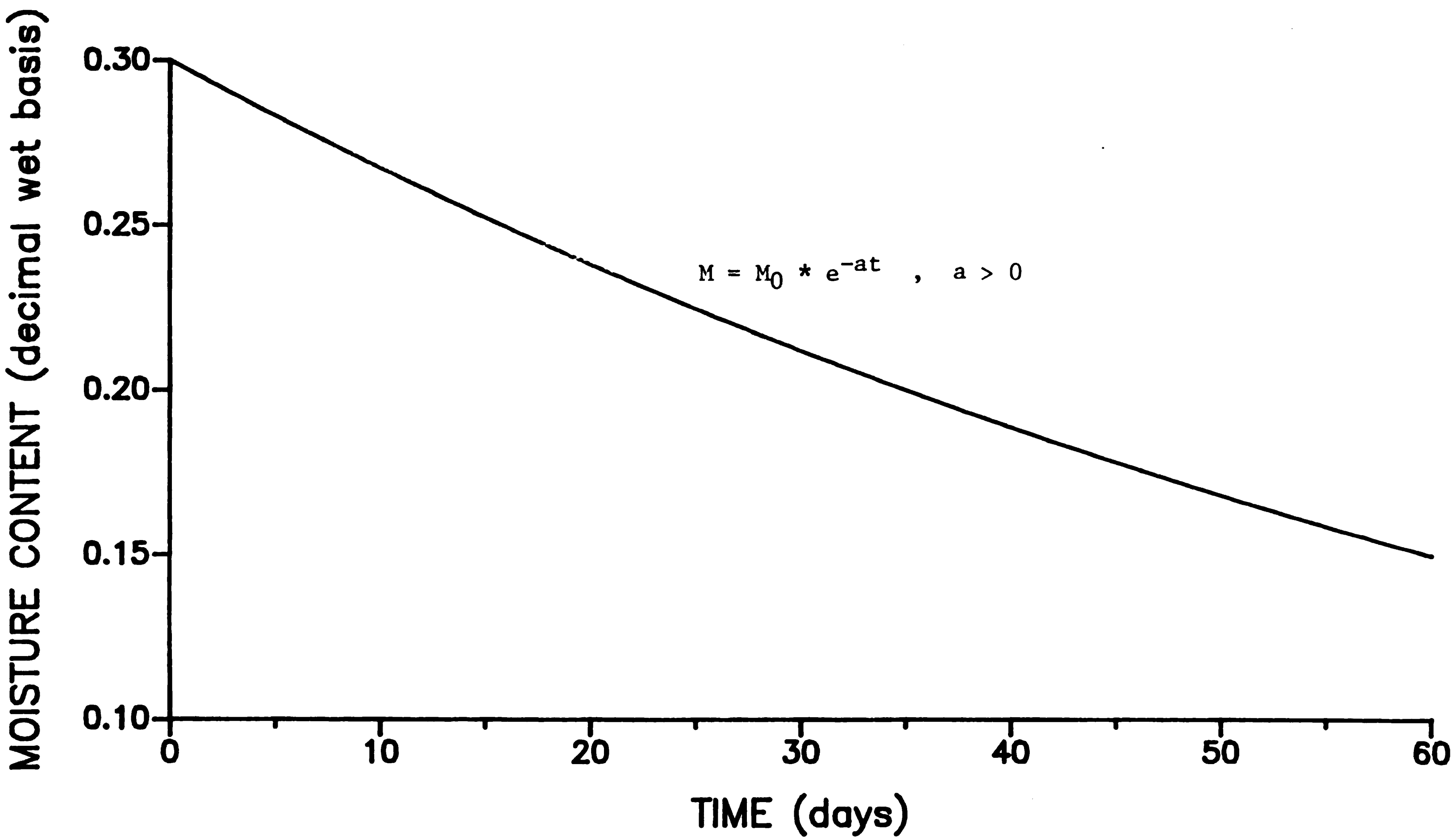

Figure 7.6 Variation in moisture content over time.

pattern as set by grains in the drying process. A linear change in moisture content over time was considered but this would not allow continuity in the rate of change of moisture at 60 days. The value of the exponential constant for each treatment stack was determined using initial and 60 day moisture levels. Equilibrium moisture content of the hay was not taken into consideration, and perhaps should have been. Estimating moisture content in this manner allows some error in that it projects an equilibrium moisture content of the hay at time infinity of 0.0%.

Density variations in the hay were assumed to be caused solely by the loss in moisture. That is, dry matter density was assumed to remain constant. This assumption is not entirely correct as some stack settling occurs (especially in wetter hay) and some dry matter loss occurs (see sections 6.2 and 7.1). However, the settling and dry matter loss changes would tend to offset one another. With the moisture and density changes over time estimated in this manner, the finite difference model developed previously was used to estimate heat generation rates.

As discussed in section 5.3, three daily mean treatment temperatures were known. The position of these known daily temperatures were approximately as shown in Figure 7.4. The temperatures were averaged to give a mean daily treatment temperature. The 30 mean daily treatment temperatures were assumed to be the temperature at the location (x=0.92, y=0.153) (Figure 7.5) and were called "target" temperatures.

The three temperature measurements were averaged to remove fluctuations in the temperature data.

Equation (7.13) was solved for the heat generation rate, G:

$$G = (T_{m,n,p+1} - T_{m,n,p} - F*(T_{m+1,n,p} + T_{m-1,n,p} + T_{m,n+1,p} + T_{m,n-1,p} + T_{m,n,p}))/B \qquad (7.29)$$

Where:

G = heat generation rate (W/m^3)
$T_{m,n,p+1}$ = target temperature at node (m,n) given by data (C)
$T_{m,n,p}$ = current temperature at node (m,n) (C)
T_{other} = current temperatures surrounding node (m,n) (C)
B = A*DT/K
A = thermal diffusivity (m^2/s)
DT = time increment (s)
K = thermal conductivity (W/m^oC)
F = A*DT/(DX)^2

The heat generation rate for a given day was predicted using immediate past temperatures calculated using the finite difference model and a target temperature for the next day. This heat generation rate was then used to calculate new temperatures throughout the stack. This procedure was repeated for the equivalent of 30 days. Ambient and target temperatures and moisture content were updated on a daily basis.

The grid size used in the finite difference model for predicting heat generation rates was determined by trying different values for the grid increment (DX) and evaluating the difference in results. A grid increment of 0.153 m was chosen. Variation in results from a grid this size as compared to a very small grid (DX=0.046 m) were minimal. Increasing the grid increment above this value, however, led to sizable error.

This method for estimating heat generation rate allows some error but the error is relatively small compared to the variation in thermal properties within a bale. Estimating heat generation rate from equation (7.29) requires the assumption that nodal temperatures surrounding the "target" node (m,n) remain constant over some time period. These temperatures are actually changing over time. As an indication of the error involved in this procedure, the difference between target temperature and the temperature calculated using the estimated heat generation rate reached a maximum of approximately 5%.

There are more accurate methods of predicting unknown thermal characteristics but the curve form of how that property (heat generation rate in this case) changes over time must be assumed (Beck, 1977). Since the form of the heat generation curve is not known, the method described here was used.

This procedure for estimating heat generation rate was repeated for each treatment listed in Table 6.1. Heat generation rate was converted from a per unit volume basis to a per unit mass basis by:

$$G2 = G / D_W \qquad (7.30)$$

Where:

$G2$ = heat generation rate (W/Kg)
G = heat generation rate (W/m^3)
D_w = density of the hay (Kg/m^3)

7.3.4 HEAT GENERATION MODEL

Heat generation rate data was obtained for each of the 37 treatments. The mean heat generation rates over the 30 day period for treatments in each experiment were analyzed using one way analysis of variance. Treatment effects on mean heat generation rates were clearly significant. Duncan's Multiple Range Test was used to determine which treatments had significantly different mean heat generation rates (Tables 7.4, 7.5, and 7.6).

Mean heat generation rates over the first 30 days in storage increase as moisture increases. This supports the hypothesis explained previously concerning temperatures in storage. Two way analysis of variance was used to determine if moisture and density effects were statistically significant. Moisture contents were divided into 5 ranges and density into 2 ranges. Moisture, density, and the two way interaction of moisture and density were each related to heat generation rate (p=.01). Therefore, any model used to predict heat generation rates would need to include each of these as potential independent variables.

Table 7.4 Mean heat generation rates for alfalfa hay baled at varying moisture and density levels (Experiment 1).

Baling Moisture (% w.b.)	Baled Density (Kg/cu m)	Heat Generation Rate[1] (W/Kg)
11.5	111	0.004[a]
14.6	175	0.020[ab]
16.9	75	0.005[a]
14.3	172	0.017[ab]
24.2	91	0.009[a]
25.4	236	0.148[efg]
27.7	106	0.047[abc]
31.0	268	0.097[cde]
30.4	128	0.069[bcd]
35.2	289	0.170[gh]
48.0	189	0.161[fgh]
43.0	302	0.214[h]
19.3[2]	233	0.009[a]
27.2[3]	252	0.106[def]

[1] Mean heat generation rate over first 30 days in storage.
[2] Propionic acid applied at a rate of 1.2% of hay weight.
[3] Propionic acid applied at a rate of 1.6% of hay weight.
[abcdefgh] Superscript letters indicate values which were not significantly different by Duncan's Multiple Range Test ($p < 0.05$).

Table 7.5 Mean heat generation rates for alfalfa hay baled at varying moisture and density levels (Experiment 2).

Baling Moisture (% w.b.)	Baled Density (Kg/cu m)	Heat Generation Rate[1] (W/Kg)
16.7	74	0.010[ab]
16.2	199	0.051[ab]
18.3	87	0.006[ab]
16.9	175	0.087[bcd]
18.3	100	0.011[ab]
17.3	191	0.049[abc]
18.4	100	0.011[ab]
20.8	202	0.070[abc]
24.5	111	-0.003[a]
27.0	225	0.102[cd]
32.7	130	0.066[abc]
32.2	273	0.153[d]
21.7[2]	228	0.015[ab]
30.2[3]	250	0.031[bc]

[1] Mean heat generation rate over first 30 days in storage.
[2] Propionic acid applied at a rate of 1.2% of hay weight.
[3] Propionic acid applied at a rate of 1.7% of hay weight.
[abcd] Superscript letters indicate values which were not significantly different by Duncan's Multiple Range Test ($p < 0.05$).

Table 7.6 Mean heat generation rates for alfalfa hay baled at varying moisture and density levels (Experiment 3).

Baling Moisture (% w.b.)	Baled Density (Kg/cu m)	Heat Generation Rate[1] (W/Kg)
23.4	101	0.003
24.0	252	0.114[ab]
30.5	175	0.125[ab]
30.5	295	0.137[b]
34.7	172	0.123[ab]
36.9	287	0.219[c]
35.0	164	0.156[b]
36.2	300	0.243[c]
29.0[2]	244	0.067[a]

[1] Mean heat generation rate over first 30 days in storage.
[2] Propionic acid applied at a rate of 1.6% of hay weight.
[abc] Superscript letters indicate values which were not significantly different by Duncan's Multiple Range Test ($p < 0.05$).

Using the database of heat generation rates for varying moistures, densities, and days from baling (1110 points total), a model of heat generation rate was developed. Again, as for the dry matter and temperature analyses, two sets of data were used. First, that data corresponding to non-chemically treated stacks and second, data from all treatments including treatments with propionic acid applied.

It was desired to express the heat generation rate as a function of moisture and density. If time from baling could be discarded without loss of accuracy, the model would be more versatile. However, a breakdown of heat generation rates by moisture and time from baling indicated that time from baling was an important factor.

Heat generation rates were averaged for each day over all treatments; a plot of heat generation rates over time illustrates the time effect on heating (Figure 7.7). Moisture and density are both decreasing slowly during storage; therefore, a model with only these two as independent variables would not allow for an increase in heat generation rate over the first several days (Figure 7.7).

Because the heat generation rate peaks at approximately 8 days, the data was "split" for model development. There is nothing magic about day 8 except that the breakdown of heat generation by time from baling showed that on the average, the maximum heat generation rate occurred on this day. Two sets of data were used in the regression procedure. The first, data set corresponded to time from baling less than 9

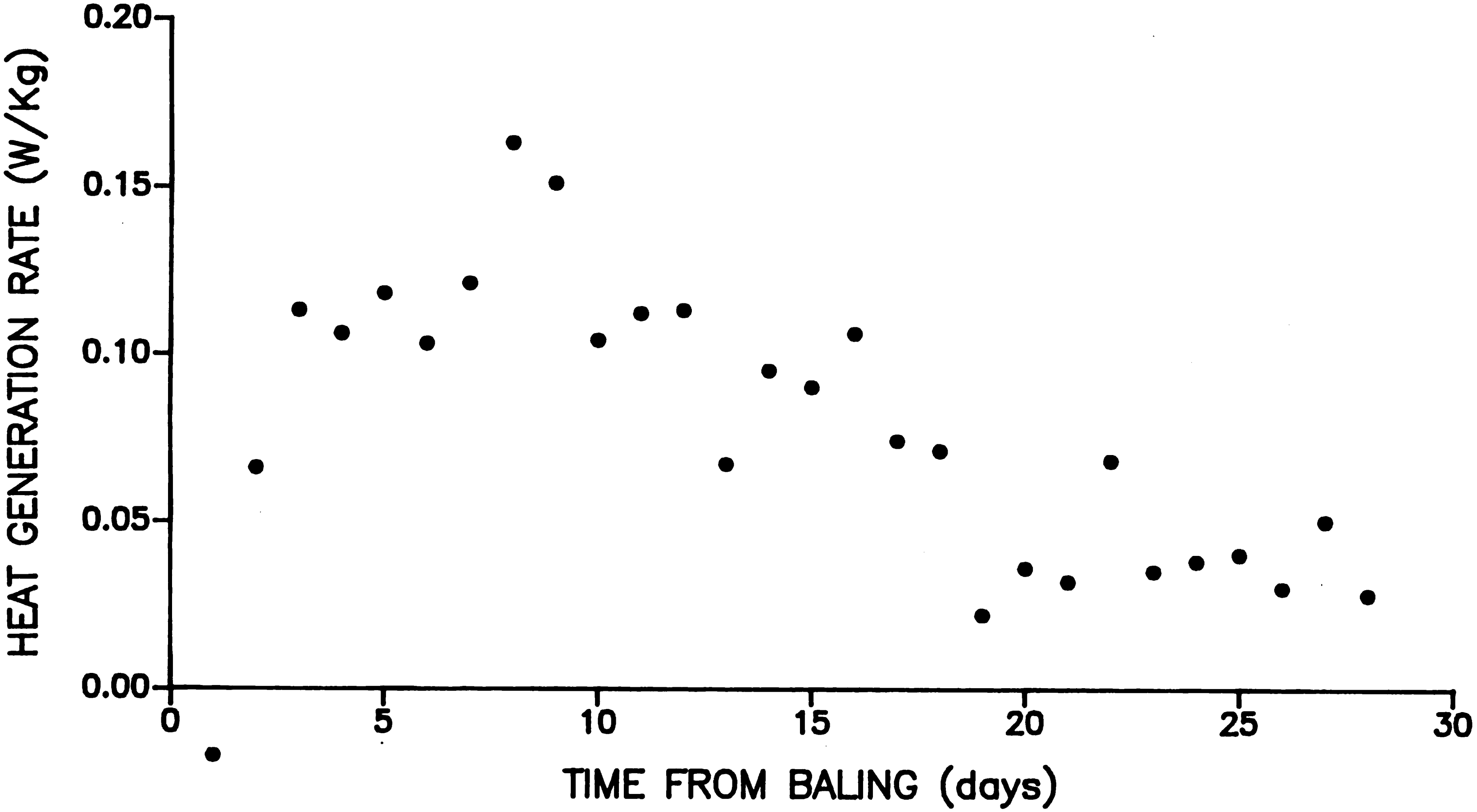

Figure 7.7 Heat generation rates of rectangularly baled alfalfa hay vs time.

days. The second data set corresponded to time from baling greater than 7 days. Data from day 8 was used in both sets to provide continuity.

Stepwise regression was used to develop the models with heat generation rate as the dependent variable. Independent variables included moisture, density, an interaction term (moisture times density), the square and square root of each of these three, and time from baling. For non-chemically treated hay, the best fit equations (p=.05) predicting heat generation rates were:

For $t \leq 8$:

$$G2 = 2.47*M^2 + 0.021*t + 0.0119*D_w^{.5} - 0.307 \quad (7.31)$$

(R^2 = .558 std. error = 0.120)

For $t \geq 8$:

$$G2 = 0.0000256*(M*D_w)^2 - 0.005*t + 0.0181*D_w^{.5} - 0.00000185*D_w^2 - 0.060 \quad (7.32)$$

(R^2 = .452 std. error = 0.080)

Where:

G2 = heat generation rate (W/Kg)
M = moisture (decimal wet basis)
D_w = wet density (Kg/m^3)
t = time from baling (days)

The equations do not provide for continuity at t=8, so to estimate heat generation rate on day 8, results from the two equations were averaged.

The same procedure was repeated with data included from all treatments with the exception that propionic acid application rate was added in the list of independent variables. The best fit equations ($p=.05$) predicting heat generation rate with propionic acid treatments were:

For $t \leq 8$:

$$G2 = 2.39*M^2 + 0.020*t - 0.088*P + 0.0126*D_w^{.5} - 0.306 \quad (7.33)$$

(R^2 = .564 std. error = 0.115)

For $t \geq 8$:

$$G2 = 0.0000145*(M*D_w)^2 - 0.004*t - 0.039*P + 0.0146*(M*D_w)^{.5} + 0.037 \quad (7.34)$$

(R^2 = .359 std. error = 0.089)

Where:

P = propionic acid application rate (% of wet weight)

Comparisons of equations (7.31) and (7.32) to equations (7.33) and (7.34) are difficult because of the difference in form; however, all models indicate that heat generation rate is increased by an increase in moisture and/or density level. Figure 7.8 illustrates the effects of moisture and density on heat generation rate for a fixed time from baling ($t=6$). For a fixed density and time from baling, heat generation rate increases as the square of moisture. Fixing moisture and time from baling shows that heat generation rate increases approximately as the square root of density in all equations except (7.34). In (7.34) heat generation rate varies almost linearly with density.

Heat generation rate increases linearly as time progresses during the first few days, and decreases linearly over time thereafter.

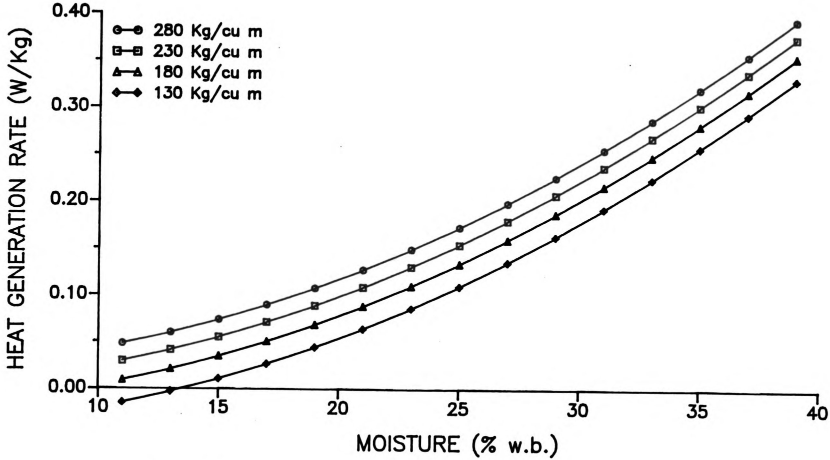

Figure 7.8 Moisture and density effects on heat generation rate in rectangularly baled alfalfa hay.

Propionic acid application decreases heat generation rate. This decrease in heating is greatest during the first several days of storage.

Heat generation can only occur with a material serving as a source of energy. That energy source in baled hay is the hay dry matter. Therefore, a relationship between dry matter lost and total heat generated should be apparent.

In a hay stack, two processes are taking place which affect the relationship between dry matter loss and heat generation. One process is the drying of the hay; this moisture removal requires heat or energy. The other process is the oxidation of carbohydrates which reduces the available dry matter in the hay. The chemical reaction for the oxidation of carbohydrates is considered to be:

$$C_6H_{12}O_6(s) + 6O_2(g) \;\text{-->}\; 6CO_2(g) + 6H_2O(l) + 2820 \text{ KJ/mole of carbohydrate} \quad (7.35)$$

In this reaction, the carbohydrate (glucose) is a solid, the oxygen and carbon dioxide are gases, and the water produced is a liquid. The water produced as a liquid must be evaporated to be removed from the stack. Taking the heat of vaporization of water (at 25 ^{o}C) into consideration decreases the amount of heat produced:

$$C_6H_{12}O_6(s) + 6O_2(g) \;\text{-->}\; 6CO_2(g) + 6H_2O(g) + 2557 \text{ KJ/mole of carbohydrate} \quad (7.36)$$

The amount of hay dry matter consumed in a hay stack can be expressed by:

$$L = D_w * V * DML * (1-MI) \qquad (7.37)$$

Where:

L = amount of dry matter lost (Kg)
D_w = density of wet hay (Kg/m^3)
DML = percent of initial dry matter lost
V = volume of the stack (m^3)
(1-MI) = Kg of dry matter per Kg of wet hay

The total heat produced in a stack of hay is the amount of dry matter consumed times the energy content of the dry matter:

$$THP = L * 14206 \qquad (7.38)$$

Where:

THP = total heat production (KJ/stack)
14206 = KJ of energy per Kg of dry matter consumed
= (2557KJ/mole * 1mole/180g * 1000g/Kg)

As mentioned previously, water is being evaporated from within the hay during storage. The amount of heat required to dry the hay is a function of the amount of moisture removed. With a storage time period of 30 days considered, the amount of heat required for moisture evaporation is given by:

$$H_{evap} = (MI-M_{30}) * D_w * V * 2433 \qquad (7.39)$$

Where:

H_{evap} = KJ of heat used to evaporate water
M_{30} = moisture content after 30 days in storage (decimal wet basis)
2433 = KJ of heat required to evaporate 1 Kg of water at 25^{o}C

The net heat released from a stack is the difference between total heat production and heat used for water evaporation:

$$Q_{net} = 14206*D_w*V*DML*(1-MI) - 2433*(MI-M_{30})*D_w*V \quad (7.40)$$

Where:

Q_{net} = heat leaving hay stack (KJ)

The net heat released can also be estimated as a function of mean heat generation rate ($G2_{mean}$) by:

$$Q_{net} = 2592*V*D_w*G2_{mean} \quad (7.41)$$

Where:

$G2_{mean}$ = mean heat generation rate over 30 days of storage (W/Kg of wet hay)
2592 = (30d) * (86400s/d) * 1KJ/1000J

Setting these two expressions equal to one another and solving for dry matter loss results in a theoretical equation relating heat generation rate to dry matter loss:

$$DML = 0.182*G2_{mean}/(1-MI) + 0.171*(MI-M_{30})/(1-MI) \quad (7.42)$$

This process could be used for any length of storage period. A storage period of 30 days was used, as the mean heat generation rate for this time was estimated.

Regression analysis was used to determine if experimental dry matter loss data and estimated heat generation rates agreed with the theoretical development. The relationship between dry matter loss and heat generation was forced to be that of equation (7.42).

Moisture content on day 30 was not measured in the experiments. To estimate the moisture content on day 30, a weighted average of initial and 60 day moisture content was used. The moisture is considered to be decreasing exponentially since the hay is drying; therefore, 30 day moisture should be closer to 60 day moisture than initial moisture. The coefficients of 1/3 and 2/3 have no mathematical basis; they were chosen as estimates.

$$M_{30} = 1/3*MI + 2/3*M_{60} \qquad (7.43)$$

Where:

MI = measured moisture content at time of baling
M_{60} = measured moisture content on day 60

Regression of experimental data was used to develop a model for predicting dry matter loss as a function of estimated heat generation rate, initial moisture content and estimated 30 day moisture content. The resulting model was:

$$DML = 0.214*G2_{mean}/(1-MI) + 0.175*(MI-M_{30})/(1-MI) \qquad (7.44)$$

(R^2 = .85 std. error = 1.83)

Neither coefficient was statistically different (p=.01) than the corresponding coefficient in the theoretical model (7.42). This close agreement between the theoretical and experimentally determined relationships validates the procedure used to estimate heat generation rate. With this relationship and the heat generation model, dry matter loss can be predicted for any size hay stack.

8. MODEL VALIDATION

The models developed in the previous chapter were developed solely from data taken in three experiments during the summer of 1985. Two sets of data were used to validate the models. The first set of data was from experiments performed during the summer of 1984. Ten different non-chemically treated stacks of ten bales each were stored during this season. Data were collected just as for this study with the exceptions that bale density was not measured and dry matter loss was evaluated after 30 days rather than 60. The second set of data was taken from an experiment which had a relatively large (100 bales) stack of hay. The data used for model validation is summarized in Table 8.1.

For each non-chemically treated stack in the first validation data set, models were used to predict a dependent parameter (eg. DML) from an independent parameter (eg. M). A linear regression was then performed with the predicted value as the dependent variable and the actual value from validation data as the independent variable. For an exact fit of a model, the intercept and slope of the resulting equation would be 0.0 and 1.0 respectively. Deviations from this indicated error in the model.

Table 8.1 Data used for validation of models which predict dry matter loss and storage temperatures.

Baling Moisture (% w.b.)	Temperature Maximum (°C)	Temperature Mean (°C)	Heating Deg. Days >35°C	Dry Matter Loss (%)
15.6	30	20	0	1.0
22.7	47	32	68	5.1
37.2	55	39	208	10.8
15.8	28	22	0	0.7
28.1	45	32	73	8.7
12.5	21	15	0	0.0
30.6	44	36	77	9.1
24.1	42	28	37	6.9
20.6	38	18	15	4.4
19.0	27	24	0	0.7
25.8[a]	35	25	1	1.0
25.9[a]	33	26	5	3.2
30.7[a]	42	37	84	11.4
33.2[a]	32	27	14	2.8
25.4[b]	36	29	2	4.7

[a] Treated with propionic acid (1% of dry matter)
[b] Data taken from a stack of approximately 100 bales. However, temperatures and dry matter loss were measured on only 10 bales from the center. Density was estimated to be 175 Kg/m^3.

8.1 DRY MATTER LOSS

Dry matter loss can be predicted from moisture content at baling from equation (7.3). Comparisons of the model predictions to actual dry matter loss indicate that this model is quite accurate. Figure 8.1 illustrates the fit of the model. Regression analysis with predicted dry matter loss (as a function of initial moisture) as the dependent variable and actual dry matter loss as the independent variable show

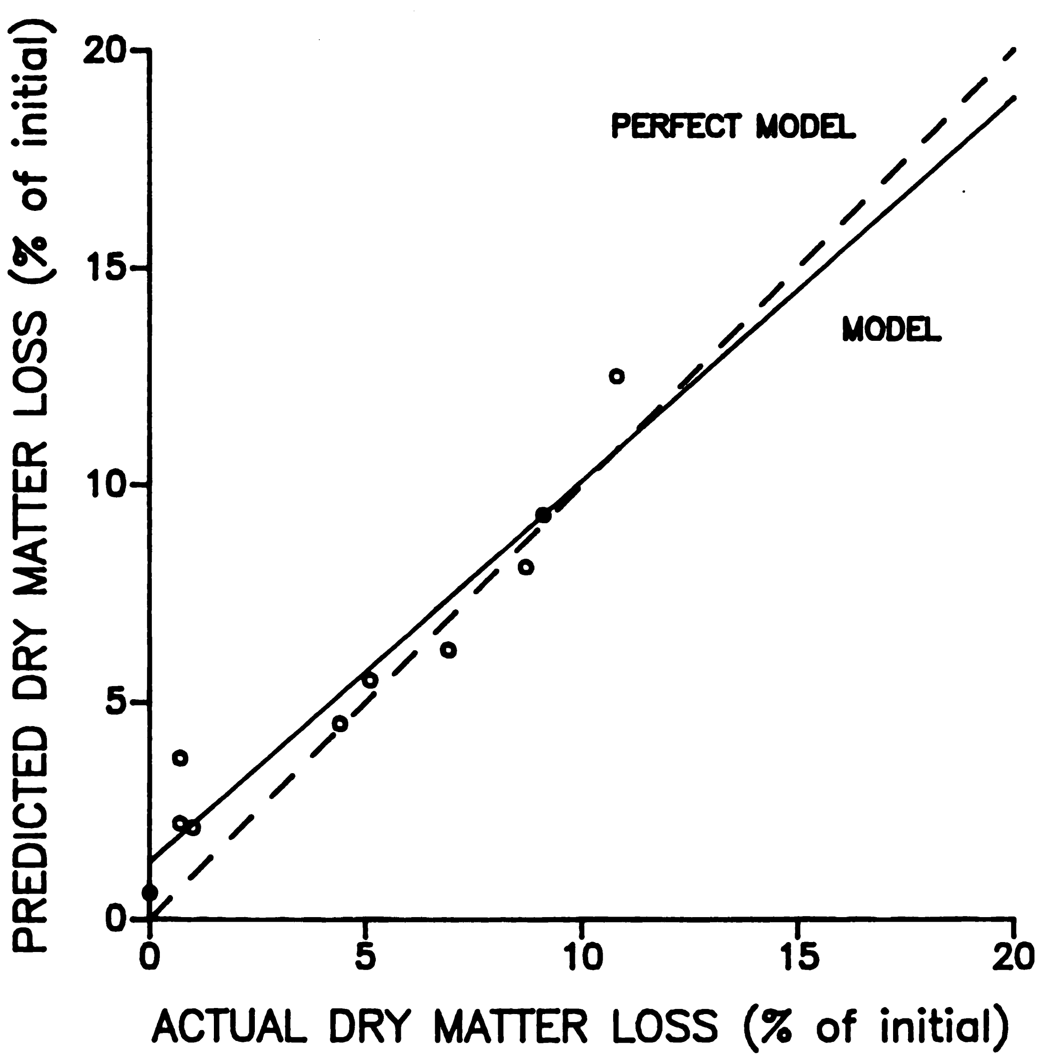

Figure 8.1 Validation of a model which predicts dry matter loss as a function of moisture content at baling.

that the slope was not different (p=.05) from 1.0; nor was the intercept different (p=.05) from 0.0. Dry matter loss for the 100 bale stack as predicted from baling moisture is 6.8%. Actual dry matter loss was only 4.7%. Perhaps the model predicting dry matter loss from baling moisture is not applicable to larger stacks. Oxygen availability in large stacks would most likely be lower than in small stacks. The oxygen limitation may in turn affect microbial activity and thus dry matter loss. More data from large stacks needs to be compared to determine if this model can be applied to large stacks.

Dry matter loss can also be predicted from maximum storage temperature or mean temperature during the first 30 days of storage (equations 7.4 and 7.5). Dry matter loss as predicted by either of these were generally higher than the actual dry matter loss (Figures 8.2 and 8.3). Slopes of the equations relating predicted dry matter loss (as a function of temperatures) to actual dry matter loss were both less than 1.0. This indicates that the models suggest more dependency of dry matter loss on temperatures than may exist. For the large stack, estimated dry matter loss values, given mean temperature and maximum temperature were 8.3 and 5.6% respectively. Actual dry matter loss was 4.7%. As for smaller stacks, using maximum or mean temperatures to predict dry matter loss led to an over estimation. The mean temperature model yielded more accurate results than did the maximum temperature model. Even though the models predicted

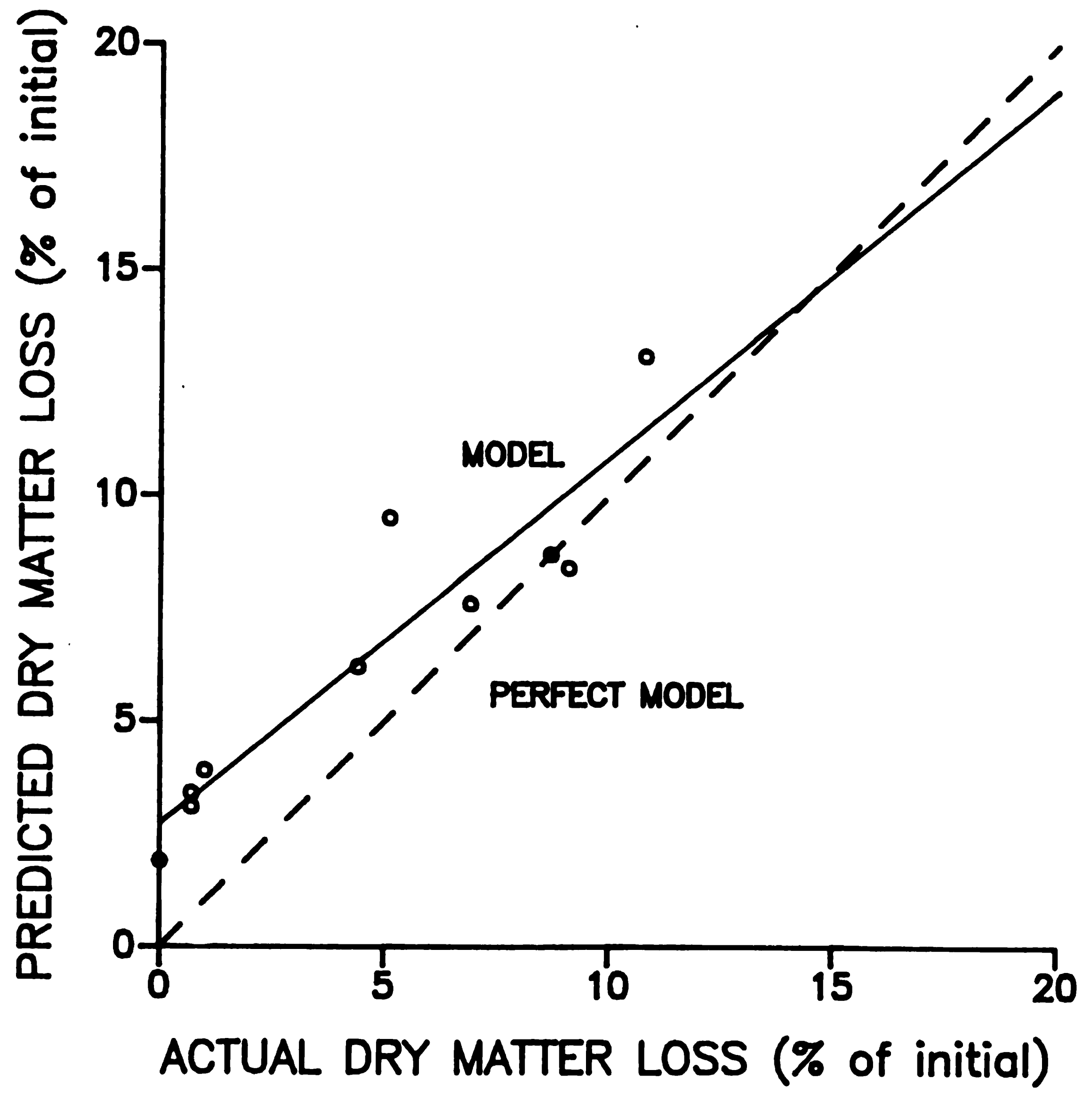

Figure 8.2 Validation of a model which predicts dry matter loss as a function of maximum temperature reached in storage.

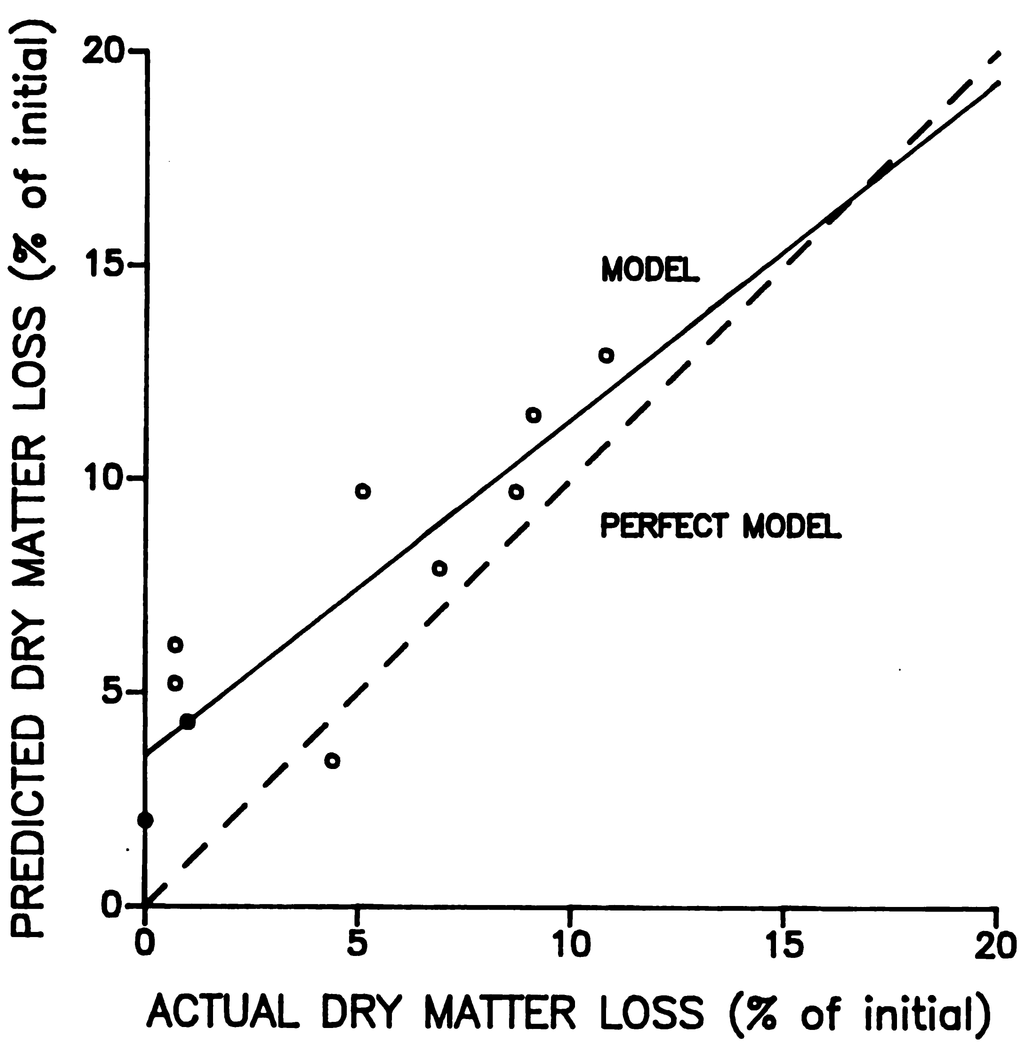

Figure 8.3 Validation of a model which predicts dry matter loss as a function of mean temperature during the first 30 days in storage.

dry matter loss greater than the actual, they do indicate correct trends.

Dry matter loss for the treatments stored in 1984 with propionic acid applied were extremely variable. Influences of propionic acid on dry matter loss (as estimated from the models) were smaller than the fluctuations in the data; therefore, no validation of the propionic acid treatment models could be done. More data needs to be collected to prove the effects of propionic acid, because the effects are small.

8.2 TEMPERATURE

The temperature models developed in section 7.2 involve moisture and density as independent variables. The validation data from the 10 bale stacks did not include density levels, so an estimated density of 160Kg/m^3 was assumed. This corresponds to a typical bale. Densities of the bales in the large stack were not known either; however, average bale weight was 23.8 Kg. With an average bale length of 91 cm assumed, the estimated density was 175 Kg/m^3.

Comparisons of predicted maximum temperatures to actual maximum temperatures (Figure 8.4) indicated error in the model. Over estimation of lower temperatures and under estimation of higher temperatures suggests that maximum temperature may increase more for increased initial moisture content than the model shows. Density tends to increase as

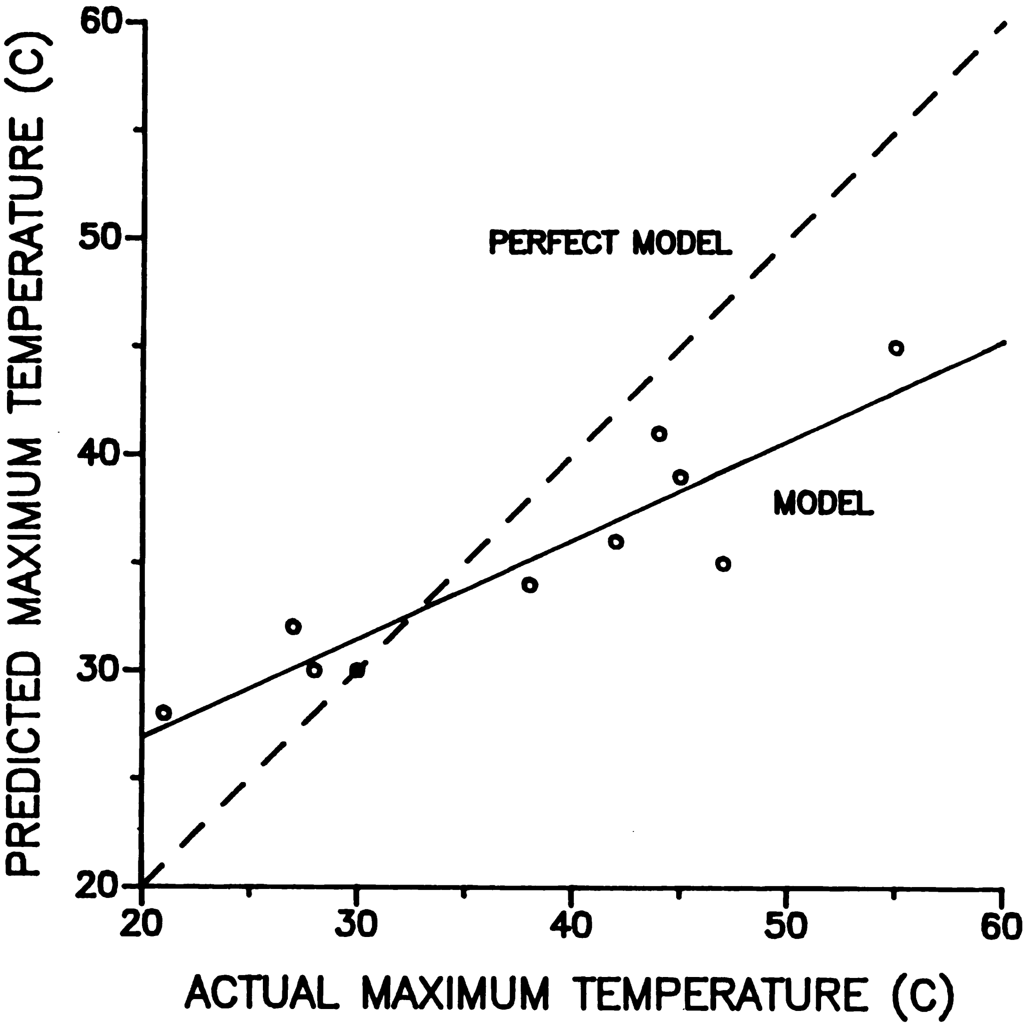

Figure 8.4 Validation of a model which predicts maximum temperature as a function of moisture content at baling and initial density.

moisture increases; if this were taken into account in the validation, model fit would be improved. Application of this model to the large stack predicted maximum temperature well. Predicted maximum temperature was 36^{o}C and the actual maximum temperature was 38^{o}C. More data should be compared to assure the validity of using this model in large stacks. A model of the heat transfer in a stack of hay including heat generation (section 7.4) would be more applicable to large stacks as stack size and structure need to be considered.

A plot of the predicted mean temperature versus actual mean temperature indicated a poor model (Figure 8.5). From this validation, mean temperature during the first 30 days in storage is more dependent upon moisture than the model suggests. Prediction of mean temperature from baling moisture and density for the large stack were reasonable but slightly low. Actual mean temperature was 29^{o}C and predicted mean temperature was 26^{o}C. This mean temperature regression model was developed from small stacks. Small stacks have more surface area per unit volume and thus can dissipate the heat more effectively. Mean temperatures in large stacks should be predicted using a heat transfer model which includes the heat generated by the hay.

The validation curve of heating in degree days (Figure 8.6) indicates large error in the model; however, with the exception of one point, correlation between predicted heating and actual heating is very high. The predicted value of degree days (63) for the larger stack of 100 bales was not

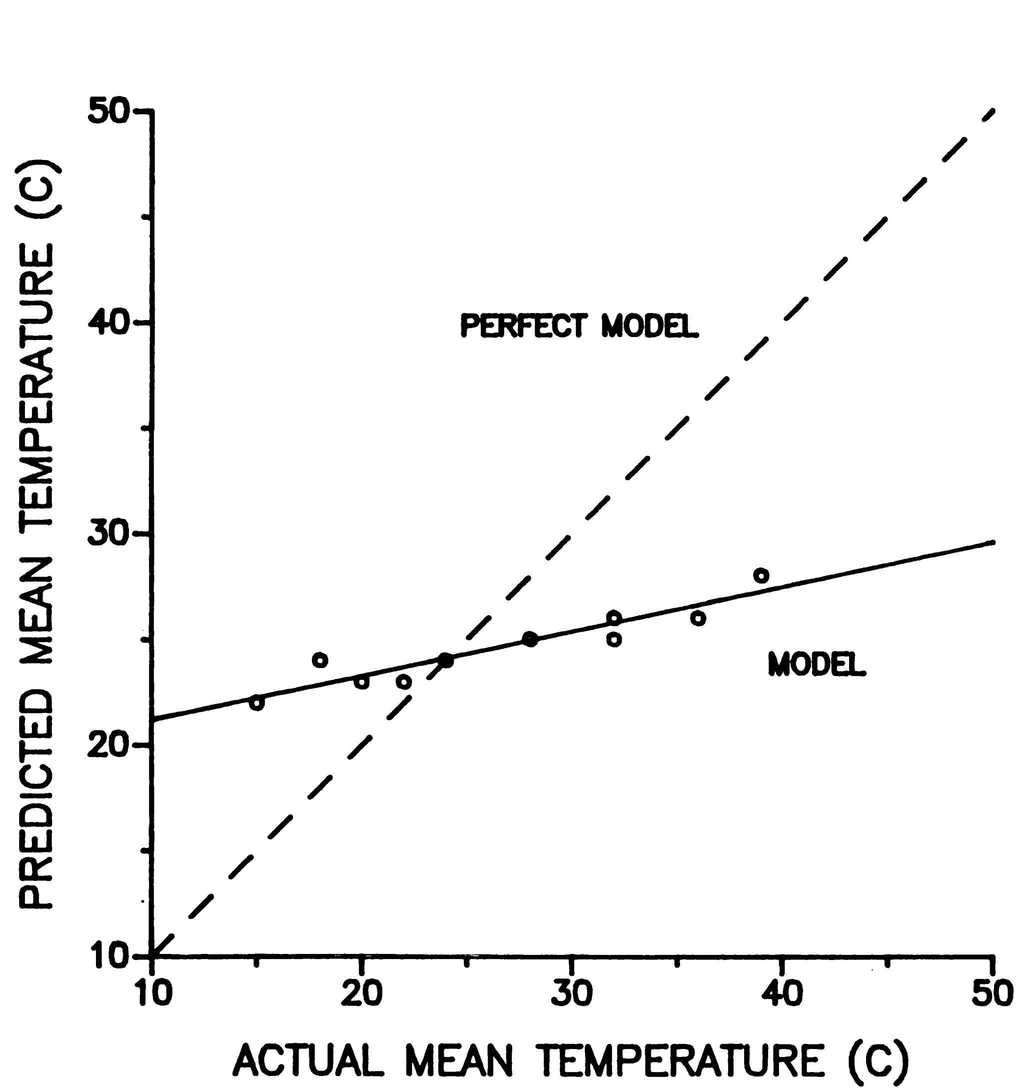

Figure 8.5 Validation of a model which predicts mean temperature as a function of moisture content at baling and initial density.

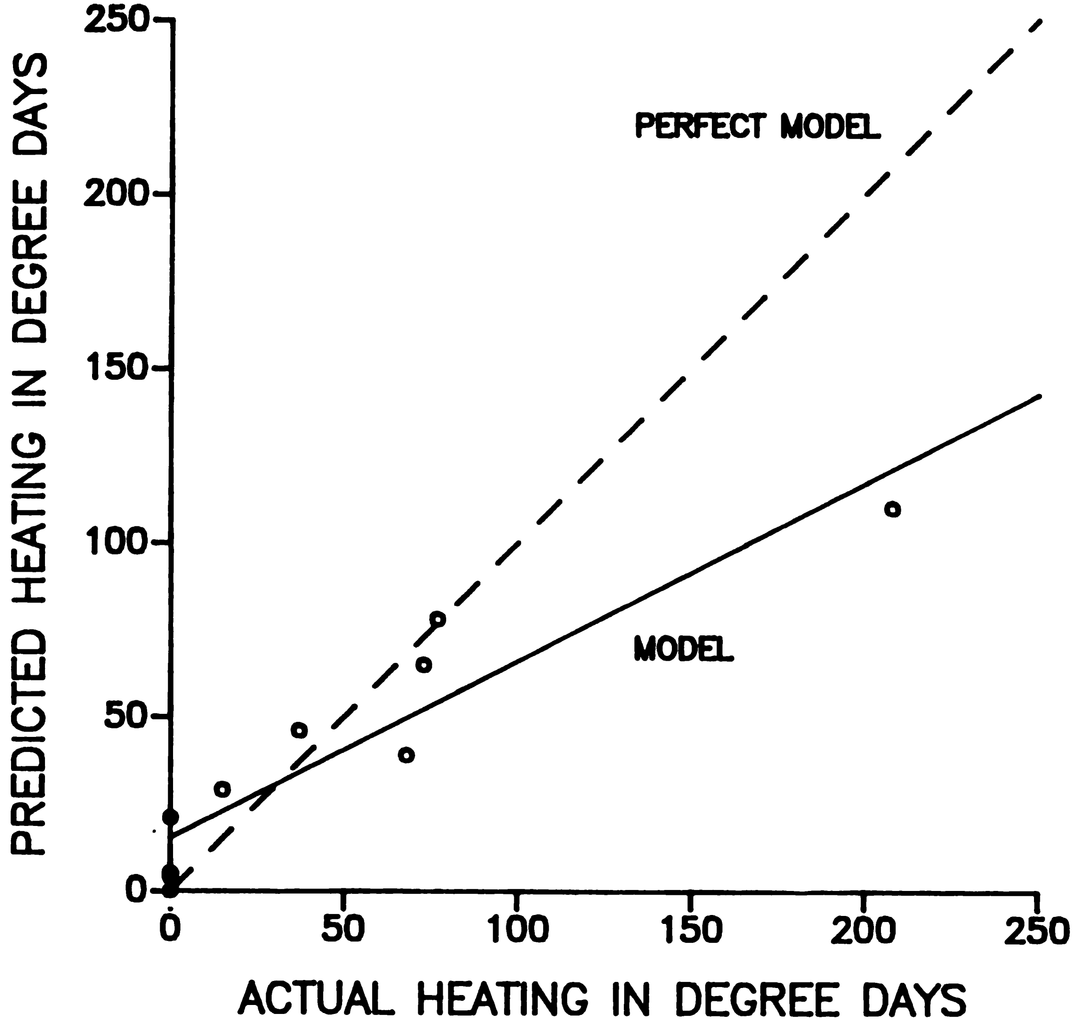

Figure 8.6 Validation of a model which predicts heating in degree days as a function of moisture content at baling and initial density.

close to the observed value (2). This indicates the need for a more comprehensive model. The large stack was stored outside, unlike the small stacks used to develop the models. Wind currents which were not an important factor for inside storage would increase heat transfer from the stack to the environment.

The models predicting storage temperatures which include effects of propionic acid were difficult to validate because of inconsistency in the validation data. Again as for dry matter loss, the predicted effects of propionic acid treatment were smaller than normal fluctuations in the data. The models did predict correct trends in maximum temperature, mean temperature and degree days, but observed values deviated from the model predictions somewhat. The deviations between observed and predicted values were less than the deviations within the validation data.

8.3 HEAT GENERATION

Heat generation rate for non-chemically treated hay can be estimated with equations (7.29) and (7.30). To be useful, these estimated values must be used in a heat transfer model of a hay stack. Validation of the heat generation model was performed by using it, in combination with the finite difference model, to predict hay temperatures in a 10 bale stack. The stack chosen for validation of the model was baled at 41 percent moisture and the density was estimated to be 225 Kg/m^3. Figure 8.7 illustrates the fit of the model. Ambient temperatures from the experiment were used in the model to eliminate any discrepancies which might be caused by differing ambient temperatures. The largest difference between actual temperatures and predicted temperatures occurs approximately 20 days after baling. The drop in temperature occurring during days 13-17 is often observed. The most important result from a temperature model of hay in storage is the maximum temperature. It is the maximum temperature which indicates whether or not the hay can be stored safely (i.e., no combustion). The model did predict maximum temperature quite accurately but did so with a time lag of approximately 3 days.

8.4 MODEL SENSITIVITY

Because the heat generation model was developed from a heat transfer model of a hay stack, accuracy of the heat transfer model directly affects accuracy of the heat generation model. Estimation of the thermal conductivity of hay was believed to be the largest source of error in the finite difference heat transfer model.

Sensitivity of the heat generation model to thermal conductivity was determined by changing the value of thermal conductivity used in the model by 10% and observing the change in estimated heat generation rate. On the average, a 10% increase in thermal conductivity yielded an increase of

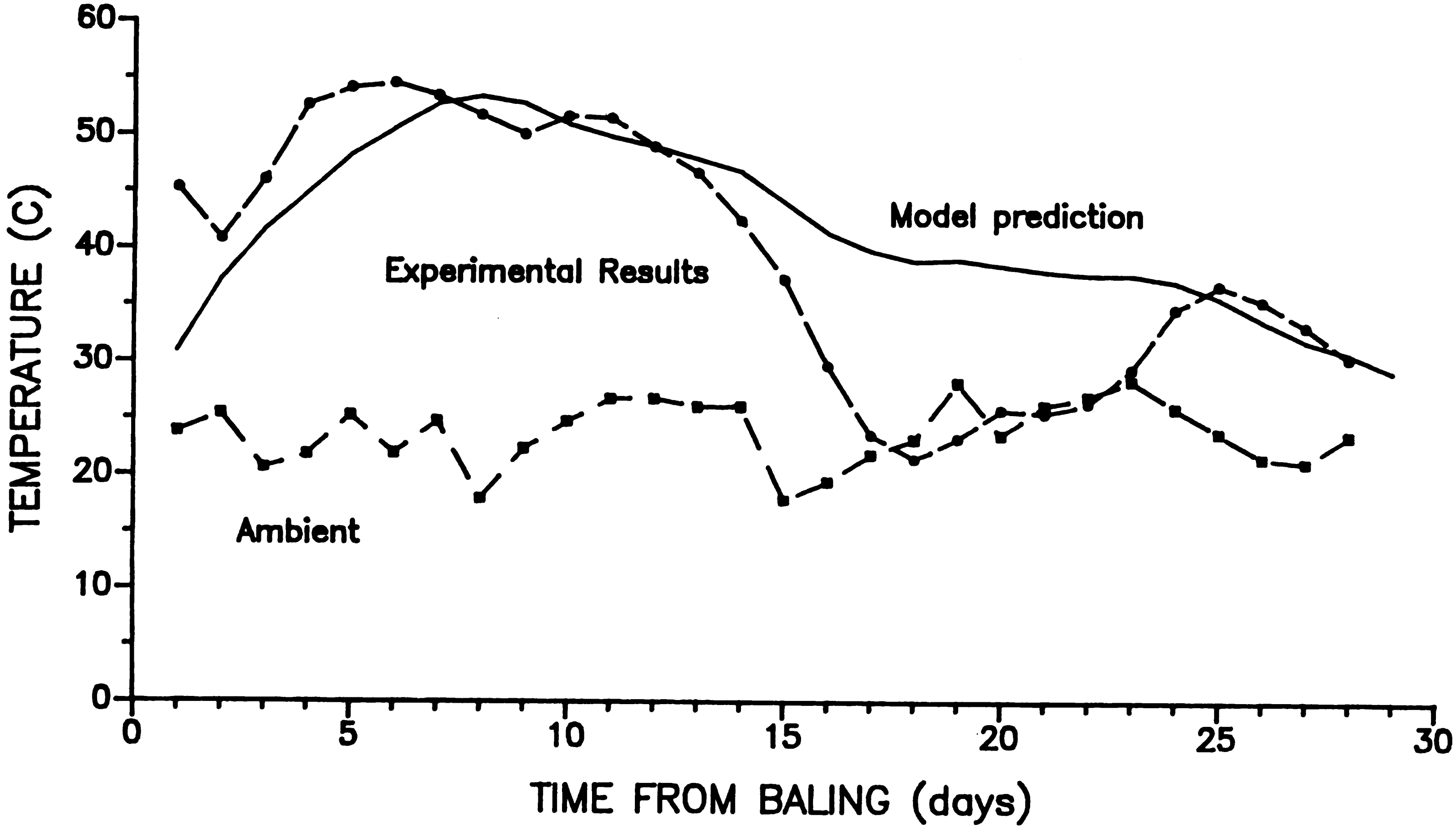

Figure 8.7 Hay temperature vs time in a small stack of rectangularly baled alfalfa hay (model validation).

6.9% in estimated heat generation rate. Similarly, a 10% decrease in thermal conductivity led to a 8.4% decrease in estimated heat generation rate.

Thermal conductivity of baled alfalfa hay was estimated from empirical relationships (section 7.3.2). From this estimation procedure, it was believed that the estimated thermal conductivity is accurate to within $\pm$ 30%. With a potential error in estimated thermal conductivity as high as 30%, the actual heat generation rate may deviate from the estimated value by as much as $\pm$ 20%.

The close agreement between the experimental and theoretical relationships between dry matter loss and heat generation rate (section 7.4) supports the assumed values for thermal conductivity. Heat generation rate was well within $\pm$20% of the value expected; therefore, the estimated values of thermal conductivity were accurate.

To illustrate the usefulness of the hay stack heat transfer model, several simulation trials of a large cubic stack (1080 bales) were run. Simulation of a stack this size yielded the same maximum internal temperatures as larger (2000 bales) stacks. Therefore, a stack of 1080 bales was used to minimize computer time.

Figure 8.8 gives the time temperature curves for three different bale conditions. Ambient temperature was set to a constant 20^{o}C. The model presented does not consider chemical reactions may which occur once the hay has reached approximately 70^{o}C. Therefore, any hay temperatures

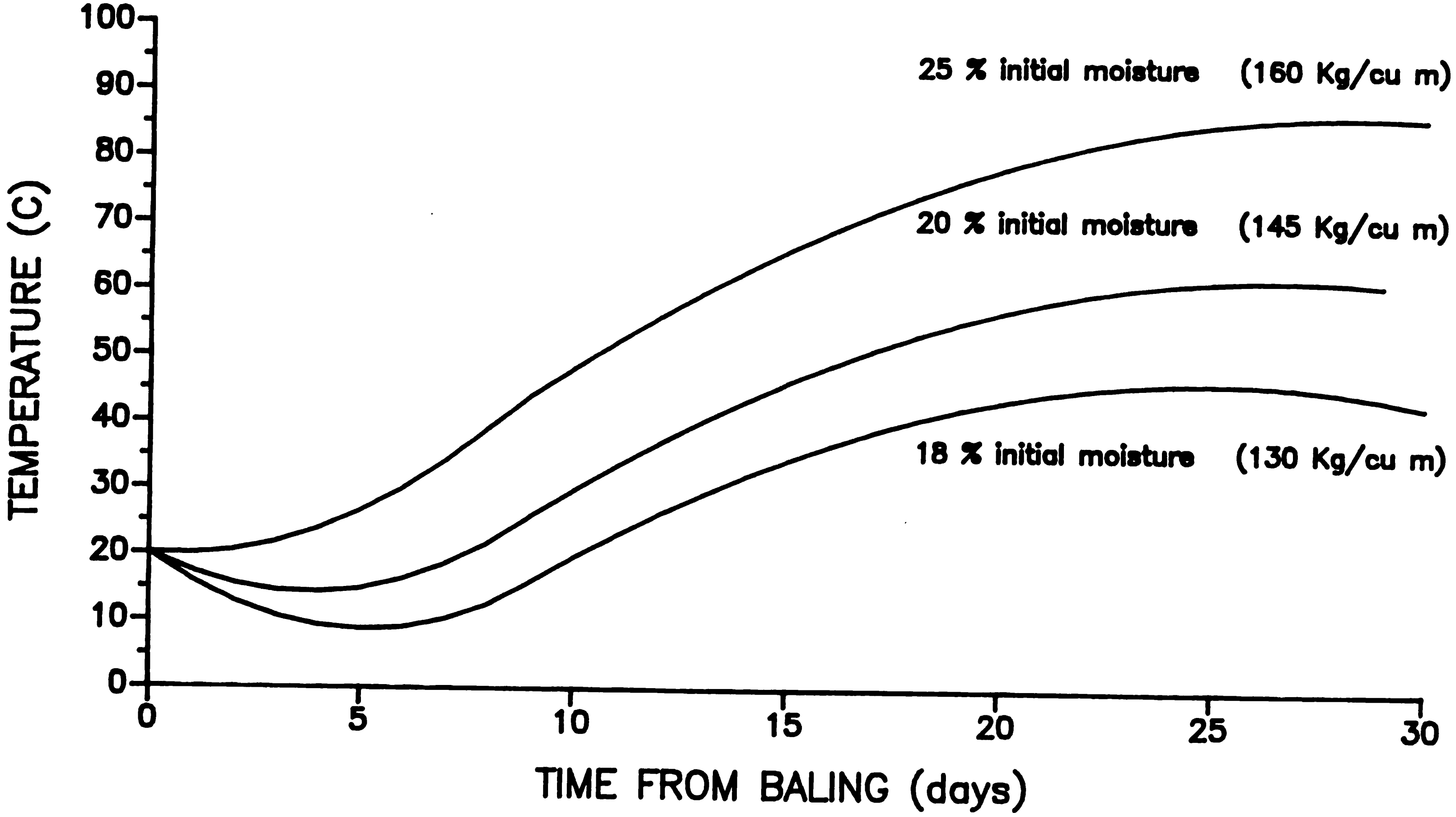

Figure 8.8 Predicted hay temperatures vs time in a large stack of rectangularly baled alfalfa hay.

exceeding $70^{o}C$ indicate that combustion may occur later in storage. With this in mind, the results in Figure 8.8 agree quite well with discussion in the literature concerning safe baling moisture limits. The model indicates that to assure combustion will not occur, baling moisture must be limited to approximately 22%.

Nutrient value decreases once temperatures exceed $60^{o}C$. The model indicates that this happens at approximately 20% moisture. Experience has shown that baling above 20% moisture often leads to quality changes.

Finally, 18% moisture is generally considered to be the limit if no quality changes or excessive dry matter losses are to occur. With a maximum temperature of approximately $46^{o}C$ predicted for a moisture level of 18%, this would be true.

Heat generation rates for hay treated with propionic acid can be estimated using equations (7.31) and (7.32). Using this model to predict temperatures in a hay stack led to results which were not expected. A simulation of hay baled with a moisture level of 25% and a density of $160 Kg/m^3$ indicated that propionic acid treatment at 1% of hay weight reduced maximum temperature by $46^{o}C$. Propionic acid does decrease temperatures but not by this magnitude. More work should be done to evaluate the effects of propionic acid on heat generation before a model of this type can be made valid.

9. SUMMARY AND CONCLUSIONS

Hay baled wet provides an environment conducive to microbial growth. Wet hay also respires more than dry hay. The combination of these two activities causes more dry matter to be lost and temperatures to rise higher in wet hay than in dry hay. As temperatures rise, nutrient degradation occurs and the possibility of combustion increases. Baling hay at moisture levels lower than 18% (wet basis) assures safe storage and minimal nutrient change; but drying hay to this level in the field results in considerable losses due to leaching, respiration and mechanical handling.

Preservatives are added to baled hay to increase the moisture limit for storage. Proven effective preservatives are organic acids and anhydrous ammonia; acids being the most common because they are safer and easier to apply. Evaluation of preservatives is done by comparing material coming out of storage which has been chemically treated with the preservative to material coming out of storage which was not treated. The results of these comparisons are limited to the experimental conditions. To make the results applicable to more situations, a more general approach is needed. However, before preservatives can be evaluated, we must have a solid understanding of what happens during storage without preservatives.

This study was performed to model the effects of moisture and density on dry matter losses and heating during storage of rectangularly baled alfalfa hay. Three experiments were performed in which a total of 37 treatments of five bales each were placed in storage. Treatment differences were in bale moisture and density levels. Propionic acid was also applied to 5 treatments. Moisture was varied from 11.5 to 48.0% wet basis; density was varied from 74 to 302 Kg/m^3. Temperatures were measured every 6 hours during the first 30 days in storage. Dry matter loss was evaluated after a 60 day storage period. Effects of moisture and density on temperatures reached in storage and dry matter loss which occurs in storage were determined. Statistical models of these effects were also developed. Models were validated through comparison with hay storage data taken previously.

Small stacks of five bales each were used in the experiments. Temperature analyses of stacks this size cannot be applied to larger stacks because small stacks can more rapidly dissipate heat to their environment. A finite difference heat transfer model was applied to small hay stacks to predict heat generation rates. Regression techniques were then used to develop a model which predicted the heat generation rate of alfalfa hay based on moisture, density, and time from baling. This model used in combination with the finite difference heat transfer model can be used to predict temperatures which occur in a hay stack of any size. Modeling the storage process in this manner removes some limitations in the process of comparing alternative storage practices.

Conclusions regarding storage of rectangularly baled alfalfa hay were:

1. Dry matter loss was not affected significantly by bale density (neither wet nor dry matter density) but was significantly increased by increased moisture level. The best fit model to predict dry matter loss from baling moisture was:

   DML = -5.4 + 48.0 * MI

   Where:

   DML = dry matter loss (% of initial)
   MI = moisture content at baling (decimal wet basis)

2. Storage temperatures were significantly increased by increases in either moisture or wet density.

3. Dry matter loss was significantly related to storage temperatures. Dry matter loss was proportional to mean temperature and the square of maximum temperature.

4. Numerical methods (as opposed to an analytical solution) must be used to model the heat transfer process for a stack of hay because thermal properties change due to the drying process. Also, solving an internal nodal point finite difference equation for heat generation rate as a function of current nodal temperatures and a known "target" temperature is a reasonable method for predicting heat generation rate in baled alfalfa.

5. Heat generation rate in rectangularly baled alfalfa hay during storage was a function of moisture, density, and time from baling. Heat generation rate reached a maximum approximately 8 days after baling and varied as the square of moisture and the square root of density. The best fit models for heat generation rate were:

For $t \leq 8$:

$$G2 = 2.47*M^2 + 0.021*t + 0.0119*D_w^{.5} - 0.307$$

For $t \geq 8$:

$$G2 = 0.0000256*(M*D_w)^2 - 0.005*t + 0.181*D_w^{.5} - 0.060$$

Where:

G2 = heat generation rate (W/Kg)
M = moisture (decimal wet basis)
D_w = wet density (Kg/m^3)
t = time from baling (days)

6. Propionic acid application at the time of baling decreased dry matter loss approximately 1.3% for each percent (of wet weight) of acid applied. The application of propionic acid also significantly decreased temperatures and heat generation rate during storage. The decrease in heat generation rate was greatest during the first several days of storage.

10. REFERENCES

ASHRAE Handbook, Fundamentals. 1981. American Society of Heating Refrigerating and Air Conditioning Engineers, Inc. Atlanta, GA.

Andersen, S.A. 1950. Automatic Refrigeration. MacLaren and Son Ltd. for Donfoss. Nordborg, Denmark.

Beck, J.V. 1977. "Sequential Estimation of Thermal Parameters". Journal of Heat Transfer. 99(2)314-321

Bern, J.C. 1964. The Specific Heat of Alfalfa. M.S. Thesis. University of Nebraska, Lincoln, Nebraska.

Bohstedt, G. 1944. "Nutrition Value of Hay and Silage as Affected by Harvesting, Processing, and Storage". Agricultural Engineering. 25(9)337-340.

Chakrabarti, S.M. and W.H. Johnson. 1972. "Specific Heat of Flue Cured Tobacco by Differential Scanning Calorimetry". Transaction of the ASAE. 15(5)928-931.

Davies, M.H. and I.B. Warboys. 1978. "The Effect of Proprionic Acid on the Storage Losses of Hay". Journal of the British Grassland Society. 33:75-82.

Hall Carl W. 1980. Drying and Storage of Agricultural Crops. pp 258-290. AVI Publishing Co. West Port, Connecticut.

Hathaway, John E. 1983. Preservatives for Baled Hay. Unpublished research paper. Agricultural Engineering Dept., Michigan State University.

Hathaway, Koegel, and Straub. 1984. Requirements for Ammonia Preservation of High Moisture Forages. ASAE Paper 84-1536. Am. Soc. Agr. Engrs. St.Joseph, Michigan.

Hoffman, E.J. and M.A. Bradshaw. 1937. "Losses of Organic Substances in the Spontaneous Heating of Alfalfa Hay". Journal of Agricultural Research. 54(3)159-184.

Jiang, Shufen, J.C. Jofriet and G.S. Mittal. 1985. Heat Transfer Properties of Whole Plant Silage. ASAE Paper 85-4005. Am. Soc. Agr. Engrs. St.Joseph, Michigan.

Johnson, J.C. Jr. and W.C. McCormick. 1976. "Influence of a Preservative on Bermudagrass Hay Stored with Approximately 16 and 24% Moisture Content". Journal of Animal Science. 42(1)175-179.

Jorgensen, N.A., P.R. Fritschel and G.P. Barrington. 1978. Preliminary Report - Chemical Treatment of High-Moisture Hay. Dept. of Dairy Science and Agricultural Engineering. Univ of Wisconsin.

Knapp, W.R., D.A. Holt and V.L. Lechtenberg. 1975. "Hay Preservation and Quality Improvement by Anhydrous Ammonia Treatment". Agronomy Journal. 67(6)766-769.

Koegel, R.G., R.J. Straub and K.J. Shinners. 1983. Ammonia Treatment of Large and Small Hay Packages. ASAE Paper 83-1534. Am. Soc. Agr. Engrs. St.Joseph, Michigan.

Martin N.P. 1980. "Harvesting and Storage of Quality Hay". New Developments in Forages. American Forage and Grassland Council.

Miller, L.G., D.C. Clanton, L.F. Nelson and O.E. Hoehne. 1967. "Nutritive Value of Hay Baled at Various Moisture Contents". Journal of Animal Science. 26(6)1369-1373.

Mohsenin, Nuri N. 1980. Thermal Properties of Foods and Agricultural Materials. Gordon and Breach, New York.

Moser, L.E. 1980. "Quality of Forage as Affected by Post-Harvest Storage and Processing". Crop Quality, Storage, and Utilization. American Society of Agronomy.

Myers, Glen E. 1971. Analytical Methods in Conduction Heat Transfer. McGraw-Hill. NY.

Nehrir, H., Kjelhard, P.M. Anderson, T.A. Long, L.D. Hoffman, J.B. Washbo, L.L. Wilson and J.P. Mueller. 1978. "Chemical Additives and Hay Attributes". Transactions of the ASAE. 21(2)217-221.

Nelson, Leon F. 1966. "Spontaneous Heating and Nutrient Retention of Baled Alfalfa Hay During Storage". Transactions of the ASAE. 9(4)509-512.

Nelson, Leon F. 1968. "Spontaneous Heating, Gross Energy Retention and Nutrient Retention of High-Density Alfalfa Hay Bales". Transactions of the ASAE. 11(5)575-600,607.

Nelson, Leon F. 1972. "Storage Characteristics and Nutritive Value of High-Density Native Hay Bales". Transactions of the ASAE. 15(2)201-205,210.

Ott, L.E. and L.W. Horbut. 1964. Thermal Diffusivity of Compressed Alfalfa Hay. ASAE Paper 64-817. Am. Soc. Agr. Engrs. St.Joseph, Michigan.

Rotz, C.A., D.J. Sprott, J.W. Thomas and J.E. Hathaway. 1983. Preservation of Baled High-Moisture Alfalfa Hay. ASAE Paper 83-1533. Am. Soc. Agr. Engrs. St.Joseph, Michigan.

Rotz, C.A., D.J. Sprott, R.J. Davis and J.W. Thomas. 1984. Anhydrous Ammonia Injection Into Baled Forage. ASAE Paper 84-1537. Am. Soc. Agr. Engrs. St.Joseph, Michigan.

Savoie P., C.A. Rotz, H.F. Bucholtz and R.C. Brook. 1982. "Hay Harvesting System Losses and Drying Rates". Transactions of the ASAE. 25(3)581-585,589.

Schaeffer, Craig C. and Neal P. Martin. 1979. Hay Preservation. Ext. Folder 489. Agricultural Extension Service. University of Minnesota.

Shepherd, J.B., H.G. Wiseman, R.E. Ely, C.G. Melin, W.J. Sweetman, C.H. Gordon, L.G. Schoenleber, R.E. Wagner, L.E. Campbell, G.D. Roane and W.H. Hosterman. 1954. Experiments in Harvesting and Preserving Alfalfa for Dairy Cattle Feed. USDA Extension Bulletin #1079.

Siebel, E. 1892. "Specific Heats of Various Products". Ice and Refrigeration. 2:256-257

Thomas, J.W. 1978. "Preservatives for Conserved Forage Crops". Journal of Animal Science. 47(3)721-735.

Waldo, D.R. and N.A. Jorgensen. 1981. "Forages for High Animal Production: Nutritional Factors and Effects of Conservation". Journal of Dairy Science. 64(6)1207-1229.

Weeks, S.A., F.G. Owen and G.M. Petersen. 1975. "Storage Characteristics and Feeding Value of Mechanically Stacked Loose Hay". Transactions of the ASAE 18(6)1065-1069.