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FORCED-AIR DRYING OF BALED ALFALFA HAY

B. F. Parker, G. M. White, M. R. Lindley, R. S. Gates, M. Collins, S. Lowry, T. C. Bridges

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ABSTRACT

Small rectangular bales of alfalfa were successfully dried using two forced-air drying systems with heat from LP gas, solar energy (with off-peak electricity on some tests) or ambient air, and with average dry matter densities of alfalfa ranging from 80 to 166 kg/m³ (5.0-10.4 lb/ft³) with average moisture contents up to 37% (w.b.). The drying rates, pressure requirements for forced flow, psychrometric data, and hay quality before and after drying are reported. The data and a developed "drying parameter" for small rectangular alfalfa bales provide guidance for design of baled hay dryers. **KEYWORDS.** Drying, Solar energy, Forage, Alfalfa, Hay, Bales.

INTRODUCTION

Alfalfa producers in the eastern United States have difficulty in consistently making high quality alfalfa hay using field curing methods. High humidity and precipitation result in slow drying of alfalfa in the field, particularly during the last stages of drying. Alfalfa quality is reduced each day it remains in the field due to sun bleaching, dew, and possibly rain. Leaf loss during raking and baling of field dried alfalfa is especially serious since the leaves contain a higher percentage of nutrients than the stems.

Quality degradation and leaf loss of alfalfa during field drying and handling are well documented. Shepherd et al. (1954) conducted an extensive study of field drying losses

in Maryland. The dry matter losses for field-cured alfalfa ranged from 4 to 15% due to plant respiration, 3 to 35% due to leaf shattering, and from 5 to 14% due to leaching by rain. These authors also found that nutrient losses during field curing were usually higher than dry matter losses. Koegel et al. (1985) measured mechanical losses during field curing and baling in Wisconsin. They reported dry matter losses ranging from 6.1 to 27.1%. Rotz and Abrams (1988) reported from Michigan studies that field curing losses were 3.2% without rain and 11.2% with rain; machine losses during raking and baling averaged 7.2%. Buckmaster and Heisey (1990) reported that "raking dry matter loss, which averaged 8%, and nutrient loss were increased significantly when raking moisture decreased". Their work in Pennsylvania was conducted on a simulated stubble at moisture contents from 11.6 to 29.3%.

These studies show that curing and mechanical losses for field-dried hay vary considerably, with a strong dependence on weather and moisture content of the alfalfa during handling and baling. In all cases, the measured losses were significant. Reducing the time required for field drying, with raking and baling taking place at a higher moisture content, would decrease these losses.

The purpose of the work reported in this article was to develop design data for a system to successfully dry small rectangular bales of alfalfa with beginning moisture contents of 30-35% and a range of hay densities.

LITERATURE REVIEW

Early studies on the drying of small rectangular hay bales with forced air were reported by Miller (1946), Hendrix (1947), and Weaver et al. (1947). Miller indicated that the rate of air flow for baled hay should be at least four times as great as that provided for long loose hay, since large quantities of air escaped between the bales. In his study, he used static pressures from 125 to 325 Pa (0.5 to 1.3 in., w.g.) with an air flow rate of approximately 0.51 m³/s per m² (100 cfm/ft²) of floor area.

Hendrix (1947) sealed hay bales in a duct with paraffin wax. His data from testing two bales indicate that with constant pressure, the air flow increased as the hay bales dried. Weaver et al. (1947) found that the resistance of baled alfalfa to air flow was "related to the water-free density of the bale as modified by some factor". Their data indicate that 85 to 95% of the variation in the pressure-airflow relationship was accounted for by dry matter density.

Davis and Baker (1951) also concluded that the pressure required to force a given quantity of air through alfalfa is a function of dry matter density. Less static pressure was required to force a given quantity of air through bales

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Drying potential is defined as the maximum weight of moisture which can be adiabatically evaporated per kilogram of dry air at a given state point. The drying parameter is defined as the average drying potential of air in the supply duct multiplied by the air flow rate per tonne with units (g H₂O/kg of dry air) (m³/m in tonne).

The authors are Blaine F. Parker, Professor, Gerald M. White, Professor, Mark R. Lindley, Research Assistant, and Richard S. Gates, Associate Professor, Agricultural Engineering Dept., Mike Collins, Associate Professor, Agronomy Dept., Steve Lowry, Assistant Director, Kentucky Agricultural Experiment Station, and Thomas C. Bridges, Research Specialist, Agricultural Engineering Dept., University of Kentucky, Lexington.

stacked on edge (defined as air entering the cut edge of the bale) as compared to flat stacking of the bales. Furthermore, the drying rate and uniformity of drying were improved by stacking bales on edge with a vertical air flow direction. Dry matter densities tested for resistance of air flow through baled hay were 128, 160, and 192 kg/m³ (8, 10, and 12 lb/ft³).

Further study of air flow through bales of alfalfa was performed by VanDuyn and Kjelgaard (1964). To seal the sides of the bales, they used a soft pliable material around the hay and compressed the hay in a test chamber. From their data they obtained the following equations for baled alfalfa (converted to SI units):

$$P = 0.072 D_0^{2.31} V^{1.60} \text{ flow into cut edge} \quad (1)$$

(stacked on edge)

$$P = 0.104 D_0^{2.31} V^{1.60} \text{ flow into side} \quad (2)$$

(stacked flat)

where P is the pressure gradient in Pa/m, D₀ is the dry matter density in kg/m³, and V is velocity in m/s. Tolzin et al. (1990) measured the pressure-velocity relationship for baled alfalfa, including adjacent cracks, for use in the validation of a finite element model of air flow through stacked bales. The finite element approach should provide improved prediction of air velocity and distribution through a bale stack with cracks.

Carson and Kreider (1988) reported on farm-operated baled alfalfa dryers in Pennsylvania. The systems they described used a fork-lift to force pallets of baled hay into a dryer chamber with reinforced concrete walls on three sides. Although the total drying and storage cost estimates seem high (approximately \$50/tonne), these systems which have been used for over 20 years, show that small rectangular bales of alfalfa can be dried by forcing heated air through the bales.

FACILITIES AND PROCEDURE

An instrumented prototype system was designed and constructed to study the feasibility of drying bales stacked flat or on edge with a range of density and with moisture contents up to 35%.

DRYER AND FIELD EQUIPMENT

A building (figs. 1 and 2) was constructed with two air ducts in the floor. Sukup fans (No. D3761, 610 mm diameter, 3.7-5.2 kW (24 in. 5-7 hp)) were placed outside the building and connected to blow air into the ducts. Air for one fan was heated with a 107 m² (1152 ft²) solar collector (for description see Parker et al., 1986) and a 22 kW (75,000 Btu/h) electric heater. The other fan was equipped with a Sukup No. VSLT 24V-PIT axial flow LP gas heater.

The inside walls of the building were covered with plywood to provide a sealed and smooth surface for packing the hay against the wall. Alfalfa bales were stacked on pallets to provide an air flow path to the entire bottom surface of each stack.

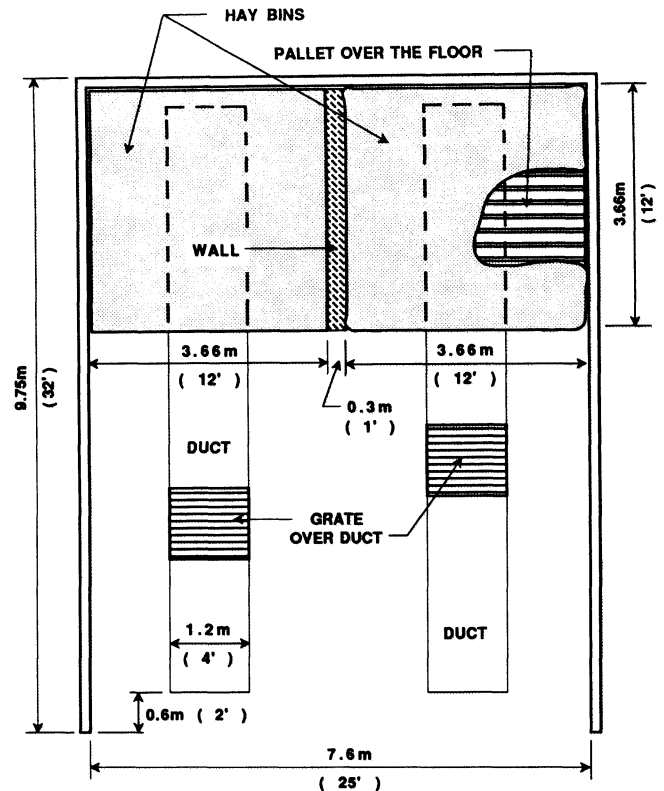


Figure 1—Plan view of the experimental hay drying buildings.

The fronts of the two stacks were open to facilitate loading and unloading the dryer. Two rectangular balloons, 0.61 m thick, 3.5 m high, and 4 m wide (2 × 11 × 13 ft) supported by a portable frame on the outside and inflated with air at 500 to 750 Pa (2-3 in. water) static pressure, were used to seal the front vertical surfaces of the stacks during dryer operation.

Field equipment consisted of a haybine, hay tedder, side delivery rake, a side cutting, plunger type hay baler, and a model 4570 Hesston hay baler with a hydraulic tensioner in 1988-89.

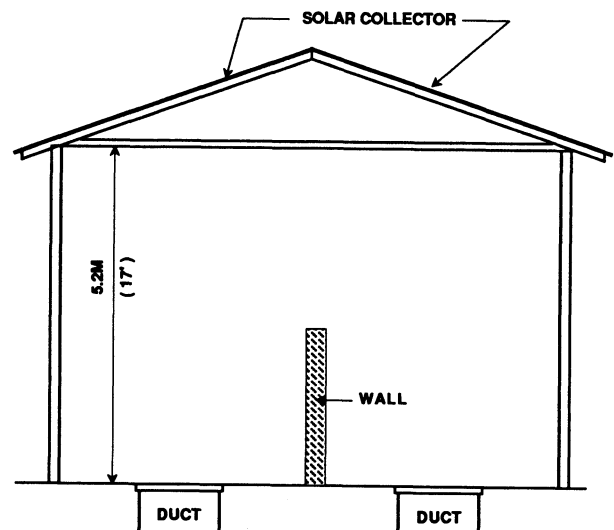


Figure 2—Front view of the experimental hay drying building.

INSTRUMENTATION

A micromanometer was used to measure static pressures. Pressure probes were made of copper tubes with 0.8 mm (1/32 in.) holes drilled at 90° spacing around the tubes and 25 mm (1 in.) apart for a 0.3 m (12 in.) distance along the tube to sense the pressure between bales. Temperatures were measured with solid state temperature probes (LM 335) which were connected to three 16-channel multiplexing cards (MetraByte EXP-16) through an A/D card (MetraByte DAS-8) in an IBM personal computer. The recorded temperatures were obtained by averaging multiple readings of each channel over 10-minute periods. Energy usage was measured using a kilowatt-hour meter along with three operational timers for the electric heater and the two fans. The rate of electric energy use by each of the timed units was obtained by measuring the incremental increase in the rate of energy use when each of the individual units was turned on.

A velocity amplifying cone (fig. 3) was constructed so that air velocity could be measured in the throat of the cone with a hot wire anemometer. The rates of airflow through bales and crevices were computed from measurements made with a hot wire anemometer in the contracted section of the velocity amplifying cone with the square base located on a bale or over a crack including a part of two bales. The hot wire anemometer and cone were calibrated with air flowing through baled alfalfa in the laboratory. It was assumed that during drying tests the same ratio of air bypassed the cone at the same measured velocity. Air bypassing the cone ranged from 30% at 0.356 m/s (70 fpm) to 36% at 1.52 m/s (300 fpm) of measured cone velocity. Measurements were difficult along the crack between the bales and the balloon because the balloon

projected over the edge of the hay. It was decided to assume that the crack flow at the balloon was the same as the average crack flow, although the flow next to the balloon appeared to be less. Air exit velocity data (obtained by taking two readings per bale and over the crevices) were used to compute air flow through the top bales and through crevices. In crevice flow measurements, the base of the cone covered part of the bale as well as the crevice. Crevice flow was computed by subtracting the average of the two adjacent bale flows from cone flow measurements made with the cone over a crevice.

BALE UNIFORMITY

Within each test, efforts were made to obtain alfalfa bales with uniform moisture, size, and density. Between tests, changes were made in the moisture content and density. The day after cutting, the progress of drying in the field was monitored with a goal of obtaining a 40 to 50% moisture content before raking. In 1988, the goal was to bale the hay at 35% moisture content and in 1989, at 30% moisture content. Test 8T2 (for test number definitions and test parameters, see Table 1) was for high density bales and test 8T4 for low density bales. The other tests ranged between these densities. In test 8T2 it was found that the Hesston baler with a hydraulic tensioner provided a much more uniform bale with square ends, so it was used for all hay bales during the remainder of the tests. After the high density baling in test 8T2 with regular bale lengths of 900 to 960 mm (36 to 38 in.), all future bales were made about 710 mm (28 in.) long for ease in manual handling. This also provided more flexibility in stacking the hay into the dryer.

BALE HANDLING AND SAMPLING

In loading the dryers, hay bales were moved from wagons into the bins in layers with sample bales placed in two or three columns (usually two columns) of each stack; therefore, the number of sample bales was two or three per layer. Since small quantities of grass and weeds were in some bales, sample bales containing mostly alfalfa were selected from locations throughout each load. The bale length and weight were recorded for each sample bale and a core sample was taken with a 38 mm (1.5 in.) diameter, shop made core sampler. The core samples were weighed, dried in an oven at 65° C (149° F) for 72 hours for moisture determination (ASAE Standard 358.2, 1988), and then ground to pass a 1 mm (0.039 in.) mesh screen for chemical analyses and/or spectral measurement with a near-infrared reflectance (NIR) spectrophotometer. The sample bales were tagged and placed in their respective sample columns. Temperature and pressure probes were placed on top of sample bales. The height of the stack depended on the stacking arrangement and the number of layers. In one instance, a limited amount of hay was available so only four layers were loaded into the dryer. In the other tests, five to seven layers were used (Table 1). As the dried bales were unloaded from the drier, the sample bales were again weighed and core sampled to obtain the moisture content and chemical analyses. The bale orientation for the different tests was varied since mechanical stacking might use either edge or flat stacking (Table 1).

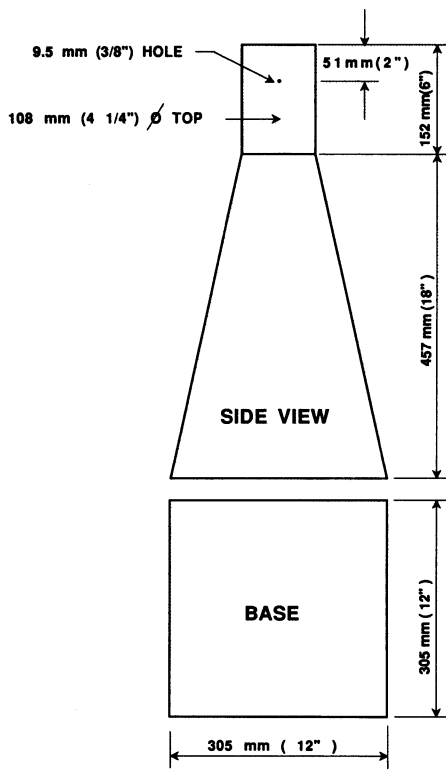


Figure 3—Velocity amplifying cone.

TABLE 1. Bale stacking, density, moisture content, air flow, and duct static pressure

Test No.*	7T2S	7T2A	7T3G	8T2S	8T2G	8T4S	8T4G	8T5S	8T5G	8T6S	8T6G	9T1S	9T2S	9T3S
Number of Bales	228	228	204	190	198	250	250	225	270	200	200	280	280	280
Depth (layers)	7	7	6	5	6	5	5	5	6	4	4	7	7	7
(m)	2.9	2.9	2.4	2.3	2.7	2.3	2.3	2.3	2.7	1.8	1.8	2.5	2.5	2.5
Bale Orientation†	AL	AL	AL	ES	ES	ES	ES	ES	ES	ES	ES	FS	FS	FS
Floor Area (m ²)	12.8	12.8	12.8	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4	13.4
Dry Matter Density (kg / m ³)														
Range	124-170	113-171	—	132-195	138-179	68-87	69-102	112-160	117-193	124-173	97-170	107-130	114-172	124-159
Average	152	150	—	166	161	80	81	136	153	147	131	120	133	138
S.D.	13.0	16.7	—	14.4	10.7	5.6	11.2	13.5	25.3	14.9	17.9	6.1	13.9	8.6
Total Dry Matter (kg)	5463	5406	5400	5162	5340	2467	2575	3814	5201	3549	3100	4193	4645	4070
Initial Moisture Content (%)														
Range	16-31	15-29	19-32	29-36	25-41	31-43	32-39	32-39	25-44	29-49	26-45	26-34	23-48	33-42
Average	22.9	23.0	24.7	33.0	31.5	36.4	37.1	35.0	32.7	33.4	32.5	28.7	31.3	36.3
S.D.	5.4	4.4	3.7	2.1	4.9	4.1	4.1	2.4	5.4	6.2	5.4	2.3	7.7	2.3
Final Moisture Content (%)														
Range	6-7	10-12	6-7	4-6	6-8	9-16	6-13	9-14	9-17	5-9	8-14	4-7	7-10	5-9
Average	6.8	11.1	6.6	4.3	7.1	11.7	8.3	10.5	10.5	6.8	11.2	5.6	8.1	6.1
S.D.	0.3	0.5	0.0	0.5	0.7	2.2	2.3	1.8	2.2	1.1	1.6	0.9	1.0	1.2
Flow Through Bales														
Total (m ³ / min)	86.9	100.3	115.2	80.7	56.9	125.6	120.5	101.2	70.5	115.8	127.5	82.1	82.3	87.1
Per Unit Area (m ³ / min m ²)														
Range	0.7-13.2	1.3-16.7	3.9-16.3	0.6-16.6	0.8-9.1	5.5-16.3	3.7-13.2	1.4-13.2	0.5-16.7	1.2-16.5	5.2-15.4	2.6-8.6	2.7-9.2	3.2-9.9
Average	6.8	8.4	9.0	6.0	4.3	9.4	9.0	7.5	5.4	8.8	9.7	6.1	6.2	6.5
S.D.	2.9	3.3	2.5	2.5	1.8	2.2	1.8	2.2	3.4	2.9	2.4	1.7	1.4	1.5
Flow Through Crevices														
Total (m ³ / min)	64.9	54.1	48.3	67.0	69.3	51.7	57.2	72.4	84.6	71.0	78.0	74.2	52.7	54.9
Per Unit Length (m ³ / min m)														
Range‡	0-6.4	0-5.1	0-4.4	0-8.0	0-6.2	0-2.9	0-3.8	0-8.1	0-7.7	0-5.7	0-4.8	0-10.2	0-2.6	0-4.3
Average	1.3	1.1	1.2	1.2	1.2	0.8	0.9	1.2	1.4	1.2	1.3	1.3	0.9	1.0
S.D.	1.4	1.1	1.0	1.0	1.1	0.8	0.9	1.4	1.5	1.0	1.0	1.2	0.7	0.8
Total Air Flow (m ³ / min)	152	154	163	148	126	177	178	174	155	187	206	156	135	142
Total Flow Per Tonne 18% M.C. hay														
(m ³ / min tonne)	22.8	23.4	24.8	23.5	19.4	58.9	56.6	37.3	24.5	43.1	54.4	30.6	23.8	28.6
Avg Duct Pressure (Pa)	576	614	548	555	577	375	343	—	—	506	481	—	697	650

* The first digit of the test number is the year (1987, 1988, 1989), the second digit is the test number in that year, S - Solar heat, A - Ambient air, G - LP Gas heat.

† (FS) refers to flat stacked bales with the largest face of the bale and the strings on the top and bottom. Edge stacked (ES) bales were rotated 90 degrees around the long axis from flat stacked. And alternate (AL) stacked bales were flat stacked and edge stacked in alternate layers.

‡ Zero flow through a crevice was obtained if the flow through the cone did not increase when placed over the crevice as compared to the adjacent bale flow.

DRYER OPERATION

The dryer with LP gas heat was used once without heat as an ambient air test. In the other LP gas tests, the heat was used to provide approximately a 15° C temperature rise continuously until the hay was either dry or the 758 L (200 gal) LP gas tank was exhausted. The dryer fans were operated continuously during the tests, except for test 8T2S, which used intermittent fan operation (15 minutes of fan operation every 2 hours) for 8 hours at night to keep the hay cool with minimal energy use when little or no drying might be taking place. Readings from the electric meters, the timers, and pressure probes in the duct and hay were taken daily. When the top layer of bales approached the target moisture level, a probe-type hay moisture meter was used to check moisture in top bales and the dryer was operated until all the top bales were dry.

DATA PROCESSING

After the bale samples were dried in the oven, they were ground, and spectral data were obtained with the NIR spectrophotometer. Using the NIR software and the spectral data of all the samples, a portion of the samples from each year was selected and chemically analyzed to establish calibration of the NIR data for *in vitro* dry matter disappearance (IVDMD, a measure of digestibility), nitrogen content (for crude protein determination), neutral detergent fiber (NDF), and acid detergent fiber (ADF). Visible mold checks were made during unloading. Statistical analyses were conducted for a paired t-test for

samples taken from the same bales before and after drying. Statistical significance was declared at the 0.01 level.

The environmental data included ambient temperature and relative humidity from a weather station [0.6 km (0.4 mile) distance from the dryer], duct temperature, the temperature on top of each sample bale as well as top surface temperatures [25 to 50 mm (1-2 in.) into the top surface] of the top sample bales and in four to eight additional bales in the top layer. The air flow rate through the hay, measured with the calibrated flow cone (fig. 3), was used to compute average air flow rates through the bales and through crevices. A computer program "DRYPOT" was developed to compute psychrometric data, heat energy added to the ambient air, the drying potential, the rate of moisture evaporation, and a drying parameter. Since the electric heat energy and the electric motor energy inputs were measured, these values were subtracted from the computed duct heat to obtain the amount of gas or solar heat added to the drying air. The DRYPOT program assumed adiabatic humidification and neglected heat generation due to respiration.

Temperature data and computed psychrometric data were plotted as a part of the analyses for developing an understanding of drying patterns, locating the drying front, computing moisture removal rate, etc. The drying parameter, which consisted of the duct drying potential (average for a given test) times the air flow rate per tonne of alfalfa, was computed as a test average. The total air flow through the bales was used in DRYPOT to compute the rate of water removal, whereas the total energy gain of

TABLE 2. Energy used, water evaporated, drying time, and DRYPOT computed parameters

	7T2S	7T2A	7T3G	8T2G	8T4S	8T4G	8T5S	8T5G	8T6S	8T6G	9T1S	9T2S	9T3S
Energy Used (kW-h / Tonne)*													
Fan	148	150	39	131	109	105	144	132	165	125	139	114	144
LP Gas†	0	0	275	351	0	491	0	425	0	663	0	0	0
Solar†	388	0	0	0	276	0	801	0	366	0	335	235	321
Electric Heat	0	0	0	0	0	0	191	0	256	0	133	153	268
Total Energy†	536	150	314	482	385	596	1135	557	787	788	642	502	733
Water Evaporated (kg / tonne)*													
	185	142	210	314	360	409	345	302	351	291	282	308	414
Tonnes of Alfalfa*													
	6.66	6.59	6.59	6.51	3.01	3.14	4.65	6.34	4.33	3.78	5.11	5.67	4.96
Energy Efficiency† (kW-h / kg H ₂ O)													
	2.90	1.05	1.50	1.53	1.07	1.46	3.29	1.84	2.24	2.71	2.28	1.63	1.77
Drying Time (h)													
Total	186	186	48	210	62	62	158	158	135	89	134	140	135
Computed†	68	49	44	126	45	26	89	75	98	48	127	118	120
Avg Drying Potential Ambient† (g H ₂ O / kg dry air)													
	2.0	2.0	2.9	2.8	3.1	3.1	1.7	1.8	1.4	1.6	1.0	1.1	1.5
Avg Drying Potential Duct† (g H ₂ O / kg dry air)													
	4.4	2.5	6.7	5.1	4.4	5.3	4.6	4.2	3.3	4.0	3.6	4.0	4.2
Drying Parameter† (g H ₂ O / kg dry air) (m ³ / min tonne)													
	99	57	166	98	262	299	172	102	144	215	110	95	120
Visible Mold													
	No	Yes	No	No	No	No	No	Yes	No	No	Yes	Yes	No

* Alfalfa in all tests was over-dried. Alfalfa weight is based on 18% moisture content (w.b.).

† Computed by DRYPOT. The computed drying time is the predicted time that the alfalfa first reached the final average moisture content, after which additional moisture removed was offset by an equal quantity of moisture gain during the night.

Note: Test 8T2S was omitted since DRYPOT computations could not be made because the fan was operated intermittently at night.

the air stream was computed using the bale flow plus the crevice flow.

Additional details on facilities and procedures have been reported in ASAE papers (Parker et al., 1987, 1988, 1990).

RESULTS

UNIFORMITY OF BALES

The uniformity of bales within each test stack and between tests as measured by dry matter density and initial moisture content for the sample bales is shown in Table 1. Baled alfalfa was dried with average dry matter densities ranging from 80 kg/m³ in test 8T4 to 166 kg/m³ in test 8T2 (5 to 10.4 lbs/ft³) with initial average moisture contents from 23% in test 7T2 to 37% (w.b.) in test 8T4G (Tables 1 and 2).

After failure to achieve the desired 30-35% moisture level in 1987 the data for 1988 (Table 1) show that the average initial moisture contents for that year were within 4% of the 35% goal for these tests. In 1989, one test was 36% with the other two near the 30% goal. No unusual procedures were used to improve the uniformity of field drying. In one case, a low wet area in the field required tedding to expose green hay so the drying rate would be closer to hay located on a sloped area. Thus, the range of initial moisture contents in Table 1 can be achieved with reasonable management of field operations.

Another factor that helped provide more uniform shape and size of bales in 1988 and 1989 was the use of a Hesston 4570 baler with a center pickup and a hydraulic tensioner. Field adjustment was much easier and a more uniform bale was obtained than with a conventional side slicing plunger type baler without the hydraulic tensioner. It was not determined whether this uniformity was due to the hydraulic tensioner or some other characteristics of the baler. Also, there may be differences in the airflow - pressure relationship for bales produced by the two balers. Additional research is needed to answer these questions.

AIRFLOW AND STATIC PRESSURE

Table 1 illustrates the range of airflow, bale densities, and stack depths for these tests. For the densities, depth, and static pressures used, the average flow velocity through

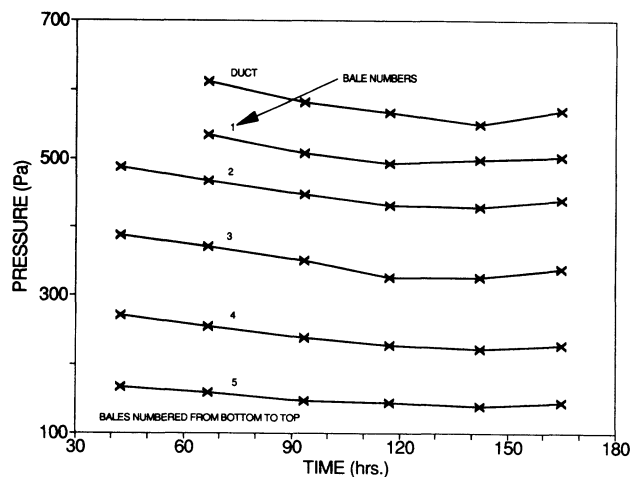


Figure 4—Static pressure in the stack vs. time for test 8T2G.

the bales as measured with the cone and hot wire anemometer system was between 0.072 and 0.162 m/s (14 and 32 fpm). The air flow through crevices was approximately 30 to 50% of the total flow.

Test results for one test showing a small decrease in pressure readings during drying are shown in figure 4. In some tests the static pressure was nearly constant during the entire drying period. This result agrees with the work of Weaver et al. (1947), Davis and Baker (1951), and VanDuyne and Kjelgaard (1964), who showed that flow through bales is mainly a function of dry matter density which changes little during a successful drying process. Average static pressure in the supply duct ranged from 343 to 697 Pa (1.4-2.8 in. H₂O) for the different tests (Table 1).

ENERGY USED

The energy used for drying computations was taken as the energy added to ambient air. This omits the drying potential in the ambient air. Table 2 summarizes the total energy used and the quantity from each source. Except for test 7T3G, the fan energy use per tonne ranged between 105 and 165 kW/h with no observable correlation with average dry matter density or average initial moisture

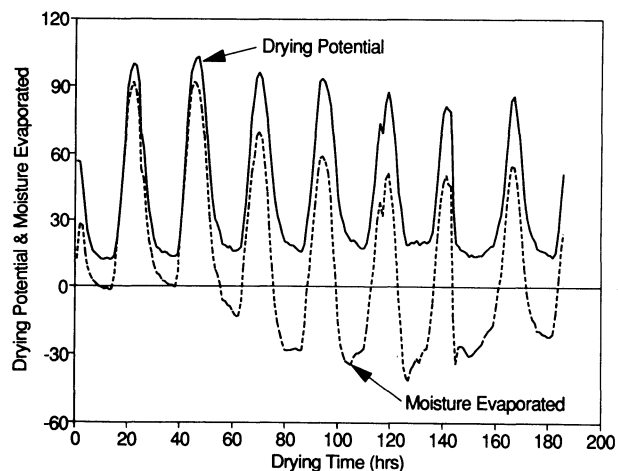


Figure 5—Computed drying potential (kg moisture × 104/kg dry air) and moisture removal rate (kg × 104/h) vs. time, test 7T2S.

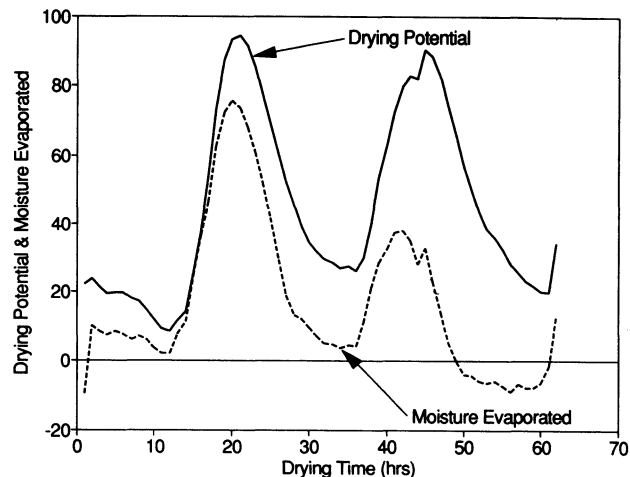


Figure 6—Computed drying potential (kg moisture × 104/kg dry air) and moisture removal rate (kg × 104/h) vs. time, test 8T4S.

content. This result may be partially due to the test requirement that all bales in the top layer be below 18% m.c. (w.b.) before ending the test as well as the lack of bale uniformity.

DRYING POTENTIAL AND WATER EVAPORATED

Figures 5 and 6 illustrate the computed drying potential and the computed moisture removal rate for tests 7T2S and 8T4S, respectively. Although the psychrometric computations are approximations, the trends in moisture movement and heat required are indicators of the drying process. Figure 5 indicates that after 68 hours of drying (Table 2), the quantity of moisture evaporated during the day was approximately equal to the moisture absorbed during the night. The system was operated an additional 118 hours to dry all bales to a moisture content below 18% (w.b.). This is an example of the results of a drying operation where the hay entered the dryer (Table 1) with a wide range of moisture content (16 to 31%) and a low average, 22.9%. Even with this low beginning moisture content, a long drying period was required to dry all bales to a safe storage moisture level and the fan energy (148 kWh/t) (134 kWh/ton) was above the average of the other tests.

Figure 6 illustrates rapid drying in a lightly loaded dryer for test 8T4S with low density bales and average initial moisture content of 36.4%. Table 1 shows that the rate of airflow through the bales was much greater with five layers of low density bales compared to seven layers of higher density bales in test 7T2S. The dryer operated only 62 hours for 8T4S compared to 186 hours for 7T2S (Table 2). DRYPOT computations for test 8T4S indicate that 45 hours were used to dry the alfalfa to a 12% average moisture content and 17 additional hours were required to equalize the moisture in the bales.

The total water evaporated per tonne and the heat energy required per kilogram of water evaporated are shown in Table 2. The water evaporated data are based on the measured moisture contents and weights of the sample bales and assumes that these bales were representative of the stack.

SEALING VERTICAL SURFACES

Observations during air flow measurements on the top layer of bales showed that placing pressurized balloons against a vertical surface was as good or better in sealing the vertical surfaces as tight packing against a solid wall. Additional research is needed to determine whether mechanical handling can be used to stack hay bales in a suitable manner for drying.

UNIFORMITY OF DRYING

The lack of uniform drying, difficulty in determining when all the bales are dry, and the inability to accurately predict drying times were operational problems. Since temperature can be used as an indication of drying activity, figure 7 (test 7T2S) was plotted as an example of bale temperatures in a vertical stack and in the air supply duct. The bales are numbered by layers from the bottom to top; layers 3 and 5 are omitted to simplify the graph. The data are plotted for six continuous days beginning at midnight after starting the test at 6:30 P.M. The bale temperatures did not follow the temperature rise in the expected sequence from bottom to top (fig. 7). For instance, bale 2 responded

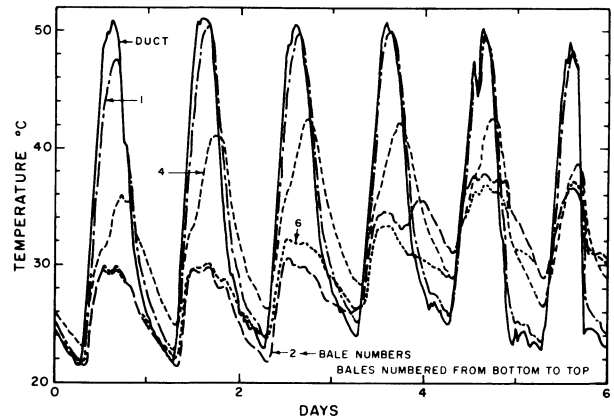


Figure 7—Duct and bale temperatures vs. time within an instrumented column, test 7T2S.

much more slowly to duct temperature than did bale 4. However, by the fifth day and certainly by the sixth day, all the bale temperatures responded similarly to the duct temperature peak, indicating that little or no drying was taking place. In fact, the alfalfa in all tests (Table 1) was drier than the 18% m.c. (w.b.) normally considered necessary for storage. Thus, the relative temperature of bales provides some guidance on location of drying activity; however, the time to stop the drying process is not accurately indicated by the temperature pattern alone. Bales frequently failed to follow the expected drying front pattern as shown for the first three days in figure 7. Moisture measurements of the top bales also showed irregular drying. For instance, for one moisture measurement of test 8T6S, 26% of samples from the top bales had moisture contents above 18% (two above 40%) and the remaining bales were dry. The next day, only 3% of the samples were above 18%. In some bales small pockets of high moisture could be located near the end of drying. The fan was operated until all top bales were measured to be less than 18%. These irregularities make it difficult to determine when all bales are dry or to develop prediction equations for drying time.

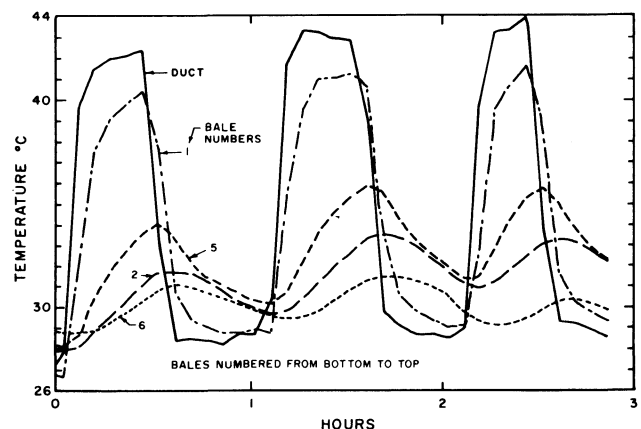


Figure 8—Temperature response of a seven layer column of dry hay to three, 30-minute heat pulses.

TEMPERATURE RESPONSE

The response time of the hay to temperature change can be used to evaluate the effect of fan cycling at night to save energy when little drying is expected with no heat. To provide information on the temperature response of dry hay, a test was conducted on a seven layer stack of dry bales with an approximate average air flow velocity (including bale and crack flow) of 0.2 m/s (40 fpm). The gas unit provided the flexibility of heating the air for short periods and then checking the movement of the heat wave through the hay. For these short heat pulses, the bale temperatures, read from the bottom bale to the top, peaked with a decreasing magnitude (fig. 8) with bale No. 2 out of sequence. The peak temperature of six top bales lagged the peak temperature of the duct by an average of 16 minutes with a range of 8 to 25 minutes.

The temperature response of hay to entering air temperature changes during drying is shown in figure 9 with the fan cycling, 15 minutes "ON" every 2 hours at night, for test 8T2S. Numbers on the graph indicate the bale layers (from bottom to top) for the sample column. This was the highest density hay dried in these tests (Table 1). The temperature pulses due to fan cycles indicate a relatively rapid response, even for the top bales. Under the conditions of this test, the hay was effectively cooled with this fan operating sequence; therefore, this cycle should be useful in keeping hay, with less than 35% moisture content, cool during the night hours (fig. 9).

QUALITY EVALUATION

The paired sample data for "before and after drying" are presented in Table 3. The only test which showed a significant decrease (at the 1% level) in quality during drying was 8T4, which was baled at the lowest density and dried in the least time (62 hours). Both the gas dried hay and the solar dried hay from this test showed a significant decrease in protein and IVDMD along with an increase in NDF and ADF (Table 3). Since the alfalfa in this particular test was dried faster than in any of the other tests and was green in color with no mold, these results cannot be explained. Bias may have been introduced during the

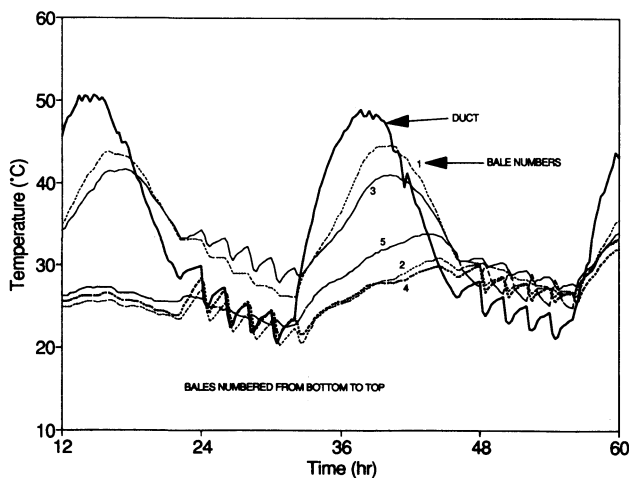


Figure 9—Temperature response of a column of hay bales during test 8T2S to temperature change with night fan cycling, 15 minutes "ON" every 2 hours.

sampling process due to the looseness and low density of these bales.

The only other data of the chemical analyses for paired samples which indicated a statistically significant change were in tests 7T4S, 8T5G, and 9T2S (Table 3). These changes do not indicate any consistent deterioration of

TABLE 3. SAS* (1988) analysis of change in quality parameters for paired and dried samples taken before and after drying

Variable	Mean Before (%)	Mean After (%)	Difference	Std Error of Mean	T	PR > T †
Test 7T2G, 14 samples.						
IVDMD	62.8	63.8	-1.03	0.55	-1.88	0.0832
PROTEIN	16.0	15.8	0.22	0.21	1.03	0.3222
NDF	48.4	48.5	-0.19	0.64	-0.29	0.7762
ADF	31.5	31.3	0.23	0.79	0.29	0.7729
Test 7T2S, 14 samples.						
IVDMD	62.7	63.4	-0.68	0.69	-0.99	0.3418
PROTEIN	16.2	15.8	0.44	0.21	2.13	0.0531
NDF	49.0	49.3	-0.22	0.72	-0.31	0.7628
ADF	31.6	31.5	0.07	0.91	0.08	0.9365
Test 7T3S, 10 samples.						
IVDMD	67.2	67.2	-0.09	0.51	-0.17	0.8672
PROTEIN	13.5	13.1	0.38	0.33	1.12	0.2906
NDF	42.7	42.8	-0.16	0.76	-0.21	0.8364
ADF	28.7	28.0	0.70	0.39	1.79	0.1076
Test 7T4S, 13 samples.						
IVDMD	60.5	60.0	0.54	0.51	1.05	0.3157
PROTEIN	11.0	11.3	-0.26	0.16	-1.58	0.1410
NDF	56.5	57.9	-1.34	0.42	-3.18	0.0079
ADF	35.5	37.1	-1.66	0.35	-4.77	0.0005
Test 8T4G, 9 samples.						
IVDMD	65.7	62.8	2.86	0.65	4.41	0.0023
PROTEIN	16.4	15.5	0.99	0.28	3.47	0.0085
NDF	44.1	46.4	-2.26	0.78	-2.88	0.0206
ADF	30.0	33.3	-3.32	0.98	-3.39	0.0096
Test 8T4S, 10 samples.						
IVDMD	66.3	63.0	3.26	0.91	3.57	0.0060
PROTEIN	17.5	15.8	1.71	0.29	5.79	0.0003
NDF	42.6	46.6	-4.03	0.92	-4.37	0.0018
ADF	27.5	32.9	-5.43	1.04	-5.21	0.0006
Test 8T5G, 11 samples.						
IVDMD	74.0	71.7	2.26	0.59	3.85	0.0032
PROTEIN	19.0	18.6	0.41	0.18	2.32	0.0431
NDF	37.9	39.5	-1.66	0.74	-2.23	0.0496
ADF	23.7	25.7	-1.96	0.65	-3.02	0.0129
Test 8T5S, 10 samples.						
IVDMD	73.9	73.0	0.91	0.62	1.47	0.1743
PROTEIN	19.2	19.0	0.19	0.17	1.11	0.2953
NDF	37.0	37.0	0.05	0.55	0.10	0.9262
ADF	23.4	24.3	-0.84	0.89	-0.95	0.3690
Test 8T6G, 8 samples.						
IVDMD	67.3	67.0	0.28	1.21	0.23	0.8254
PROTEIN	15.9	15.8	0.09	0.24	0.36	0.7274
NDF	44.8	45.2	-0.33	1.13	-0.29	0.7822
ADF	31.0	31.4	-0.41	1.18	-0.35	0.7398
Test 8T6S, 8 samples.						
IVDMD	68.2	68.1	0.08	1.09	0.08	0.9418
PROTEIN	16.3	16.1	0.16	0.20	0.82	0.4385
NDF	43.4	43.3	0.17	0.99	0.17	0.8722
ADF	27.2	28.4	-1.22	1.14	-1.08	0.3180
Test 9T1S, 20 samples.						
IVDMD	69.4	68.9	0.48	0.48	1.00	0.3295
PROTEIN	18.1	18.3	-0.22	0.14	-1.58	0.1316
NDF	37.9	38.9	-0.98	0.61	-1.61	0.1246
ADF	29.2	29.6	-0.37	0.45	-0.82	0.4207
Test 9T2S, 21 samples.						
IVDMD	69.1	67.7	1.37	0.39	3.51	0.0022
PROTEIN	14.5	14.8	-0.32	0.12	-2.66	0.0151
NDF	41.8	44.3	-2.49	0.62	-4.02	0.0007
ADF	28.8	29.6	-0.82	0.44	-1.87	0.0765
Test 9T3S, 21 samples.						
IVDMD	69.2	68.7	0.55	0.41	1.35	0.1910
PROTEIN	13.9	14.0	-0.12	0.11	-1.05	0.3071
NDF	38.7	39.2	-0.50	0.50	-0.99	0.3320
ADF	28.5	28.7	-0.28	0.26	-1.07	0.2990

* SAS is a registered trademark of SAS Institute Inc.

† The mean difference is declared significant for values < 0.010.

quality during the drying tests. If one considers the 5% confidence level, test 8T5G indicates a small degradation. Therefore, it is concluded that any decrease in quality during these drying tests was minor.

Results of mold evaluation observations were: a musty odor with some visible mold for the ambient air dried test 7T2A; variable mold on bale layers 2 through 6 for tests 8T5S and 8T5G; small amounts of mold on 4 bales for test 9T1S and 5 bales with some mold for test 9T2S. The hay with this limited mold was judged to be of adequate quality for feeding dairy cows by the University of Kentucky dairy herdsman. However, since horses have a low tolerance for mold, the hay dried in tests 7T2A, 8T5G, 9T1S, and 9T2S was considered unsuitable for horse feed.

DRYING PARAMETER

The association of the drying parameter with visible mold (Table 2) shows a relationship which may be a useful design criterion for rectangular bale dryers. Visible mold occurred with the average drying parameters of 57, 95, 102, and 110, whereas no visible mold occurred in two samples with drying parameters of 98 and 99 (Table 3). With a drying parameter value above 120, no mold was observed. Apparently this drying parameter changes from a possibility of mold to no mold in the vicinity of 110. Although future research is needed to establish a definite relationship, it would appear that this drying parameter may be useful as a design criterion.

SUMMARY AND CONCLUSIONS

Small rectangular bales of alfalfa hay were successfully dried using forced air with initial moisture contents up to 37% m.c. (w.b.) at dry matter densities from 80 to 166 kg/m³ (5 to 10.4 lb/cubic ft). Although a range of moisture content and density can be dried, the alfalfa in a single drying stack should be as uniform as can be achieved in normal field drying and baling. The influence of the type of baler and the use of hydraulic tensioners on bale uniformity, and the pressure-velocity relationship for air flow through bales need additional research.

The experimental dryer used in this study provided air flow and heating rates which were apparently adequate to dry alfalfa for feeding dairy cattle. Since horses are highly sensitive to mold, the levels of air flow and heat were marginal or inadequate for drying alfalfa for use by horses. Thus, the dryer as used, with air flow through cracks of approximately 30 to 50% of the total air flow, defines an approximate low limit of heat and air flow for drying alfalfa with no mold.

The drying parameter (drying potential multiplied by the flow rate per unit mass of alfalfa) correlation with visible mold in these tests provides an approximate guide for its use in the design of rectangular bale dryers. Additional research is needed to establish the economic relationships and the specific role of the drying parameter in the design of dryers.

The exposed vertical surfaces of the hay stack, were effectively sealed with pressurized balloons using a pressure higher than the air supply duct, thus providing one open side for manual or mechanical loading and unloading of the dryer.

The response of alfalfa bales to temperature changes in the air being forced through the stack was sufficiently rapid

to keep the hay cool at night when the fan was cycled "ON" 15 minutes every two hours.

The energy used for drying showed little variation with average initial moisture content or average dry matter density (Tables 1 and 2). The energy used in these tests is probably excessive since all of the alfalfa was over-dried in order to be sure that all bales were dry. With field variability between bales, some over-drying will probably always be necessary if all bales are to be sufficiently dry for safe storage.

Evaluation of *in vitro* dry matter disappearance, nitrogen content, neutral detergent fiber, and acid detergent fiber indicated no consistent significant change in quality, excepting one unexplained deviation in test 8T4.

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