SOME RESULTS OF BARN CURING OF BALED HAY WITH HEATED AIR

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Introduction

The value and applicability of barn hay driers has been well established in the major hay producing regions of the United States and other countries, where numerous barn hay driers were installed in 1930's and 1950's[9]. Most of these hay drying installations are being used for long, loose hay while some of them are used for drying chopped hay. With the development and wide application of hay balers in the United States, the success experienced by many farmers in drying long and chopped hay raised considerable interest in drying baled hay, which resulted in a reasonable success by a few farmers in drying baled hay with systems designed for long hay and chopped hay. The drying system has remained essentially the same, except for minor modifications which experience has shown desirable.

Several reports on the drying of baled hay have been published in U.S.A. WILEMAN[20] reported in 1946 on his tests of drying baled hay placed on a slatted floor with an air flow of 2.7 to 2.85 m^3/min per sq meter of floor. He described that the moisture content of hay, when baled, should be 35 per cent or less and around 6 m^3/min per sq meter of floor should be used. He concluded further that hay should be placed on the drier within two hours after baling to prevent heating. MILLER[10] (1946) reported the successful experience of a farmer named Herbert Muffly in designing, constructing and operating a baled hay drier. The fan provided 3 m^3/min per sq meter of floor area. WEAVER[19] (1947) and SHEDD[16] (1947) carried out some field tests on drying baled hay with forced air in North Carolina and in Iowa (U. S. A.), respectively. Although HENDRIX[4] (1947) and DAVIS, Jr[3] (1951) studied on the fundamentals of drying baled hay with the experimental equipment, it appears that further studies on the effects of varied drying conditions such as air volume, air condition, initial moisture content of the hay and method of stacking on the drying rate have not been established.

In Japan, farmers have been intent on harvesting their hay crops and storing the crops under the best possible conditions, but sufficient or adequate information regarding artificial drying of hay is not available at the present time. Thus, additional basic studies on barn hay drying are sorely in need.

Thus, the author[8] (1969) has carried out field observations of a duct system barn hay drier with unheated air ventilation for long hay. The investigation was carried out at the Trappist Monastery in Oshima-Tobetsu, Hokkaido in 1958-1959. From the results of the survey on unfavorable climatic conditions for hay making in Sapporo, Hokkaido, OKAMURA *et al*[11~15] recognized the necessity of artificial drying of hay and they further studied drying of baled hay using slatted floor type barn driers with unheated air, and also using a tunnel and Venta floor system with supplemental heated air in 1962-1965 in Sapporo and Obihiro, Hokkaido, respectively.

These studies suggested that supplemental heat might be neccessary for drying baled hay using slatted floor type barn driers.

The purpose of the present paper is to report on one phase of baled-hay-drying investigations conducted during 1965 at the Experimental Field of Hokkaido University, which included determination of the performance of dryer for baled hay, uniformity of drying and variations of moisture content and temperature in bales.

Materials and procedure

1. Drying System

The baled-hay drying installation used in this study was installed upstairs in an existing dairy barn with a width of 10 meters and length of 28 meters. The installation was composed of a side main duct air distribution system and a slatted floor, a portable drier and a flexible connecting tube. The air distribution system consisted of a main duct 11.7 meters in length, which was placed along one side of the mow with a slatted floor of 76 sq meters in floor area which was carried on joists resting on the mow floor. The joists were spaced at 60 cm intervals. Wide cracks at the mow floor level extend along one side of the main duct throughout its length. Air was forced from the main duct through cracks and into the space under the slatted floor. The air then was forced between the slats of the slatted floor into and through the hay. The slatted floor extended to within about 60 cm of the edge of the effective mow space. The static pressure built up by the fan was utilized chiefly by causing a flow of air through the baled hay with a minimum of loss in the duct and slatted floor.

A special portable drier (Lister Drier) which consists of an axial flow fan with a 100 cm diameter rotor to provide air, driven by a 40 hp aircooled diesel engine was used for this work. In order to establish a satisfactory connection between the drier unit placed on the ground 10 meters from the barn and the main duct on the mow floor of the barn upstairs, a flexible nylon airtight tube 100 cm in diameter was used.

2. Materials

The hay for the drying tests was first-cuttings of orchard grass with red clover, regarding data are shown in Table 1. This hay grown on a 40 ha farm was cut with tractor mounted mowers on June 29 and 30. At this time the moisture content of the growing orchad grass and red clover was 70.0 and 81.0% w. b. respectively. All moisture contents, as given in this paper, have been calculated on a wet-basis. After cutting the hay was conditioned with a hay conditioner and was left in swaths during the first day. During the second day, the hay was deluged by rainfall. Baling was carried out with a field pickup baler on the third day (July 2) and the fourth day (July 3). The size of bales was 36×48×76 cm, or a volume of 0.13 m^3. The weight of bales ranged from 17.4 to 21.0 kg, with an average weight of 17.7 kg, about 133 kg/m^3 in density and the total weight of 1810 bales stacked on the mow floor was 32.1 tons. The bales were laid on edge and each layer of bales was laid crosswise on the layer below. The barn was filled on July 2 to 3, 1965, to a depth of ten tiers of bales. The bales were carefully stacked to keep the surface of the piles of bales aproximately level. The moisture content of bales ranged from 28 to 41 per cent, with an average moisture content of 38.1 per cent.

TABLE 1. Initial data on baled hay

Type of hay	Average plant height (cm)	Average weight ratio (%)	Average moisture content (% w. b.)	Average yield of raw material (ton/10 a)
Ochard	100	79.7	70.0	
Red clover	35	13.2	81.0	2.8
Weeds	50	7.1	—	

3. Operating the fan

The fan was started on July 2, when 741 bales were stacked on the slatted floor to a depth of 4 tiers of bales, and was operated 12-13 hours daily from 7 : 00 a. m. to 8 : 00 p. m. The fan was operated for a total of 140 hr and 38 min., and was stopped on July 14 when curing of the hay was adjudged to have finished.

4. Methods and Equipment

(1) Moisture content

Samples of hay were taken from three bales at six selected points (A–F) of each tier of bales, to determine the moisture content of baled hay. Sampling of hay was done two times, at the beginning and conclusion of the drying test. An average moisture content of samples was regarded as the average moisture content of the entire bales. The vertical and horizontal distributions of moisture content in the hay mow were estimated from the results of moisture content of these samples. In addition, other samplings for moisture determination were carried out at six points of the 9th tier of bales, with five replicates, to determine the drying rate of the entire baled hay mow, during the drying test. All hay moisture content determinations were carried out by a 103°C, single stage, 24-hr oven method and are expressed in percent of wet basis[1].

(2) Atmospheric conditions

Temperatures and relative humidities of air were recorded at the outside of the barn (at the fan inlet), inside of the main duct and at two points above the hay mow (for exhaust air) by four hair thermo-hygrometers, which were calibrated by an Assman's aspiration thermo psychrometer, during the drying process. The temperature in bales was measured by inserting an ordinary earth thermometer into the bales, to determine the variations of the bale temperature, and also to evaluate the effect of blanking plate on raising entering air tenperature during the fan operation. This was done at six points at which a sample for the moisture determination was taken, on July 7 and 9. Since the fan of Lister drier provided 4 sheets of blaking plates, the effects of the blanking plate on air volume control and raising of the air temperature were evaluted by measuring the air flow rate entering the mow floor and by determining the temperature and humidity of air at the inlet and outlet of the drier fan.

(3) Air flow volume and static pressure

Numerous studies of air distribution, air flow, and static pressures in a main-duct-with-laterals system and in a main-duct-with-slatted-floor system were reported by WEAVER, HENDRIX[6], SHEDD (1946), STEINBREGGE[17], BRUHN[2] STERE[18], DAVIS (1974) and the author (1969), using long and chopped hay. Air flow characteristics in drying baled hay with forced ventilation were observed by WILEMAN (1944), MILLER (1946), and DAVIS (1951). As for the drying system in this paper, OKAMURA etc[12,14] (1963) reported their experimental results on the static pressure distribution in a baled hay mow with unheated air using an electric motor driven axial fan with 1060 mm of diameter, which was connected directly to the main duct. The Over-all performance of a forced-ventilation system for hay drying is rather difficult to measure in a manner which permits satisfactory comparison with other driers under different conditions. Therefore, in order to determine the effect of the blanking plate and flexible tube on the controlling of the air flow rate and air distribution in the main duct, the air flow rate and static pressure were measured. The volume of air flow through the system was calculated by the average air speed at the drier inlet and inlet area, and static pressure was measured by a pitot tube installed in the main duct and by a manometer.

(4) **Fuel consumption**

Fuel for the engine unit was directly supplied from an auxiliary commercial drum can, and determining of fuel consumption was carried out by measuring decreased depth of fuel in the drum can.

Results and discussion

OKAMURA[13] reported in 1964 on his tests of drying baled hay on the slatted floor which was used by the author in this study, with an air flow of 9.0 m^3/min per sq. meter of floor. Unheated air was supplied by a 15 hp motoer-driven, axial-flow fan rated to deliver 720 m^3/min at static pressure of 20 mm aq. Bales were made from first-cutting mixed orchard and clover hay containing between 25 and 30 per cent of moisture and the average density of bales was 150.5 kg/m^3 (converted value at 20 per cent moisture). The barn was filled to a depth of four tiers of bales, or about 145 cm. The fan was operated for 178 hr, from July 6 to 25, to evaporate 10% of moisture content, or 1.9 ton of water, from 14.7 tons of hay. The electric power consumption was 984 kWh, and the cost of power in this case was reported to be 300 yen (1964) per ton of dry hay. Table 2 gives the data collected by the author in the tests during the season of 1965.

From Table 2 it may be recognized that using heated air 1810 bales, about 32 tons of total weight of hay, were dried from 38.1 to 18.2 per cent of moisture in 140 hr, resulting in 10.7 tons of water removal. The fuel consumption was 940 litters, and the cost of fuel was calculated to be 876 yen (1965) per ton of dry hay. Although this cost seems cousiderably higher than that of drying with unheated air as described above the over-all performance of a forced-ventilation system for hay drying is rather difficult to measure in a manner which permits satisfactory comparison with other tests

TABLE 2. Summary of tests on barn curing of baled hay with Lister Drier, 1965

Date		July 2—July 15 1965
Total fan operation hours (hr)		140.51
Total fuel consumption (l)		940
Fuel consumption (l/hr)		6.67
Before drying	No. of tiers	10
	No. of bales	1810
	Total weight of material (kg)	32100
	Average weight of bales (kg)	19.2
	Average size of bales (cm)	36×48×76
	Average density of bales (kg/m³)	133
	Average moisture content (%)	38.15
After drying	Total weight of hay (kg)	21400
	Average weight of bales (kg)	11.8
	Average moisture content (%)	18.27
Amount of fuel per ton of dry hay (l)		43.8
Fuel cost per ton of dry hay (Yen/l)		876
Total weight of water evaporated (kg)		10700
Rate of water evaporation (kg)		76.6

under different conditions. This was pointed out by HENDRIX[5] (1946).

All the hay baled and dried in this test was of good final quality considering the rainfall it encountered in the field. There was no mold, evident to the eye in any of the bales, and the aroma was good.

1. Performance of blanking plate

The manufacturer of the Lister drier recommended that when the atmospheric relative humidity was exceptionally high, 2, 3, or 4 blanking pieces should be attached to the fan inlet, which would result in reducing the airflow volume and increasing the air temperature by baffling the fan. During the drying period in this study several observations were made on the fan operating performances by attaching the blanking plates. Table 3 shows the relation of numbers of blanking pieces attached to the fan, air flow and static pressure under the present test conditions. It is recognized that when the numbers of blanking pieces were increased both the air flow and static pressure decreased promptly. In Table 4 are shown the results obtained from the observation made on temperature and relative humidity of the entering of outdoor and main duct air. From Table 4 it may be seen that using the blanking plates has a significant effect on raising the temperature and reducing relative humidity of the intake air. However, for

TABLE 3. Relation of No. of blanking plates to airflow volumes and static pressures

No. of blanking plates	Air volvme (m^3/min)	Static pressure (mmAq)
0	900	20.9
1	810	18.6
2	675	12.5
4	170	1.9

TABLE 4. Relation of No. of blanking plates to air temperature and relative humidity in the main duct

No. of blanking plates	Temperature (°C)		Relative humidity (%)	
	Outdoor	In the duct	Outdoor	In the duct
0	18.0	20.0	87	83.5
2	18.0	23.0	87	69.0
4	18.0	27.0	87	55.0

most cases, it is not practical to use more than three blanking pieces because sufficient air to properly dry the hay will not be being forced through the bales. It is agreed that when it is raining or when we have humid weather one or two blanking pieces are to be adapted.

In the drying tests of bales, the blanking plates were not used and a static pressure of 20 mm of water remained in the main duct. The air flow at this pressure and at 1830 rpm of the fan, according to the result of this experiment, was 900 m^3/min for ten tiers of bales. Reference to the manufacturer's catalog curve of fan characteristics shows that this fan operating against a static pressure of 20 mm of water should be delivering nearly about 1000 m^3/min when running at 1830 rpm. This indicates that the air volume, as determined, was too low. This difference of air volume might be caused by the long flexible air tube connected between the main duct and fan and by differences in measuring devices and methods. Air velocity readings were taken at 16

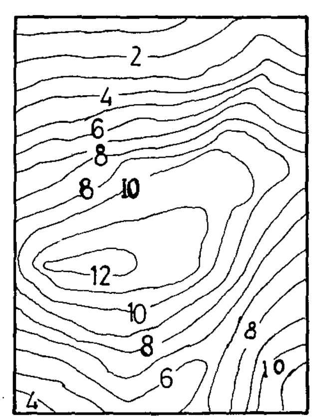

Fig. 1. Air velocity cotours at a cross section ofthe main duct in front of the start of slatted floor openings. View looking downstream of the air flow.

points of cross sections of the main duct and in front of the start of the slatted floor openings. Velocity contours were then drawn as shown in Fig. 1 at 1-mps intervals.

2. Drying process in the drier

Since the author found in his study on drying long hay with a duct system drier at the Trapist Monastery, that the hay of about 30 cm depth flom the surface of hay mow dried last, the moisture content of six bales at 9th tier were continuously observed during the drying period to predict the drying process of entire bales and to predict the completion of drying. (Fig. 2). From Fig. 2 it can be seen that the average moisture content of the six bales decrease as drying progress, but the moisture content of individual bales show different curves, and that there is a hay-damping process at the beginning of the drying period.

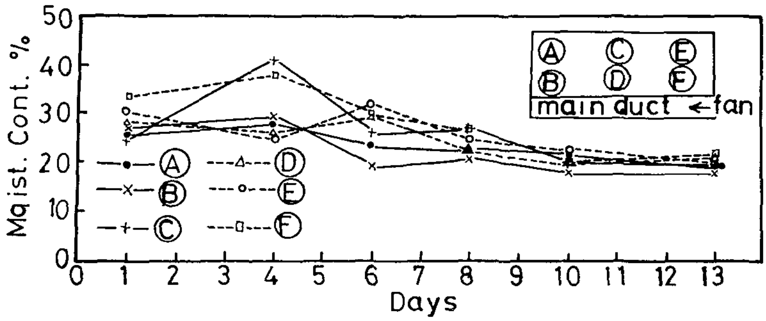

Fig. 2. Rate of moisture reduction of hay bales at 9th tier, July 3 to July 15.

Atmospheric conditions of temperature and humidity which were determined outdoors, in the main duct and over the bale mow during the drying period are shown in Fig. 3. The intermittent solid line shown at the lower portion of the graph shows total time during which the fan was in operation. The mean temperature and the mean relative humidity outside the drier system was 17.6°C and 77.7% respectively. These atomspheric conditions might be adequate for barn hay drying without heated air. But, as will be noticed by examination of Fig. 3 the mean relative humidity in the main duct during the fan operating time was lowered by 4-10% and the mean temperature was raised by 3-4 degree C from outdoor conditions at the starting of the drying period, and the difference in relative humidity and temperature between the inside and the outside of the main duct decreased with the progress of drying. Lowering the relative humidity and

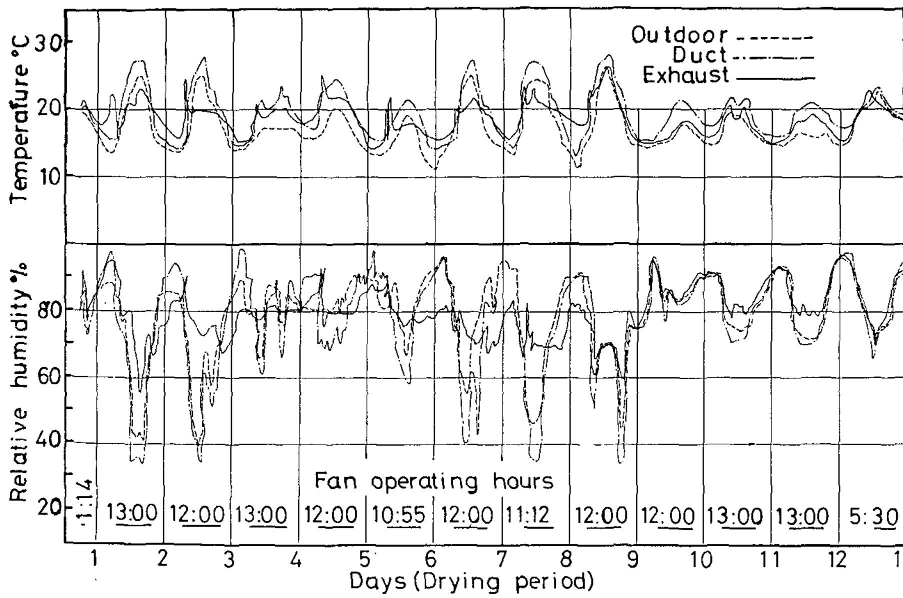

Fig. 3. Temperature and relative humidity of the outdoors, duct and exhaust air during the drying period with fan operating hours.

raising the temperature of airflow were due to air heating by engine exhaust gases, and this is regarded as one of special features of the Lister drier.

Observation shows that both the temperature and the relative humidity of the exhaust air from hay bales immediately after starting the fan was raised up to 27°C or thereabouts and was lowered by continuing the fan operation. Sometimes, this temperature was lowered below outdoor temperatures during fan operation, but the relative humidity was not lowered below the outdoor relative humidity. Alternatives of temperatures or relative humidities outside of the dryer, at the inside of the main duct and at the top of the bale mow show similar curves with the progress of drying, and the difference of temperature or relative humidity at each measuring point becomes less and less. From this fact it can be predicted that the drying was nearly completed.

3. Variations of moisture content in hay bales

An average moisture content of 10 tiers prior to and after drying was plotted against each selected point (A–F) (Fig. 4). The curves shown in Fig. 4 indicate the average horizontal distribution of moisture contents in all bales at the biginning and completion of the drying tests. From Fig. 4 it

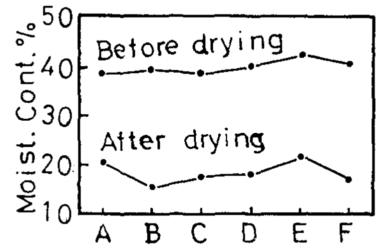

Fig. 4. Average horizontal distribution of moisture content in bales, prior to and after drying period.

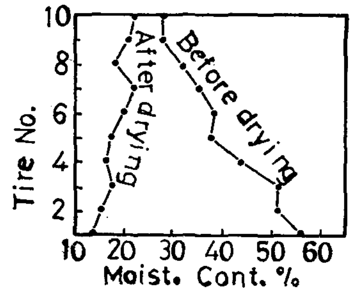

Fig. 5. Average vertical distribution of moisture content in bales prior to and after drying period.

may be recognized that the average moisture content at each point shows various values before drying, but it can be equalized, to some extent by drying, with the exception of A and E points which show rather higher moisture contents compared with other points. The observations of moisture content distribution for the horizontal plane were found to consist of the results of the horizontal distribution of static pressures in hay bales reported by OKAMURA[13].

An average moisture content of bales at the selected 6 points (A~F) prior to and after drying was plotted against each tier of bales (Fig. 5). The curves shown in Fig. 5 indicate the vertical distribution of average moisture content in all tested bales at the biginning and completion of drying. From Fig. 5 it may be recognized that when bales were stacked on the floor the moisture content of the upper tiers were lower than that of bottom tiers, but at the end of drying the moisture content of the upper tiers were rather higher than that of the bootom tiers.

Since baling is usually started in the morning and continues to the evening, it may be natural that earlier baled hay has a higher moisture content than hay baled later, so that before drying, the moisture content of the bottom tier is rather higher than that of the upper tiers. However, this trend of moisture distribution is desirable for drying with a slatted floor type barn hay drying system, because the rate of drying is larger at the bottom of the bale mow.

The moisture content of bales is an index to determine the completion of drying, and the observations of vertical distribution of moisture content shown in Fig. 5 revealed that samples should be taken from surface tier of bales. Similar results were reported previously by the author in observations of vertical distribution of moisture content for long hay drying with a duct system barn hay drier.

4. Temperature in bales

A certain amount of heat is usually generated in the long or chopped hay[7] and in the center of the bales which have a higher moisture content after stacking in the barn and the temperature in bales rises to considerable height. It is understood that this temperature rise is restricted by the cooling effect of the fan operation. It may be added that this cooling effect is one of the advantages of forced air drying of hay bales. As described previously, the fan was started in the morning and stopped in the evening in this drying test.

Temperatures in the center of bales, at selected 6 points in 9th tier in the same manner as described above, in the moisture determining test, were measured on July 7 and 9. The temperature in the bales immediately after stacking in the barn and before starting the fan were from 22 to 30°C with a mean value of 26°C showed that a certain amount of heating had already started in all bales on July 7. On July 9, these temperatures were from 21 to 24°C showing that when the fan was turned off over night on July 8, the temperature rise in the bales decreased with the progression of drying and by fan cooling.

The average temperature variations in the 9th tier during the fan operat-

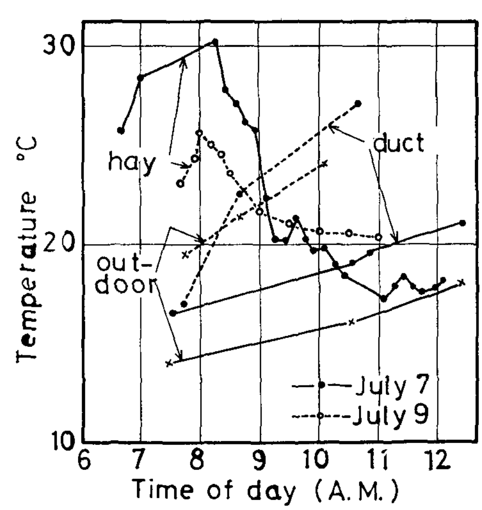

Fig. 6. Comparison of temperatures in the bales with entering and exhaust air temperatures on July 7 and 9, as related to time of day.

ing period on July 7 and 9 are shown in Fig. 6 with plotted curves of atmospheric temperature variations. From Fig. 6 it may be seen that temperatures in the bales rise during the early part of the fan operating period and drop below the entering air temperatures within 300 and 40 minutes after starting the fan. This means that the fan operating time, required for cooling heat generated in the bales is shortened by a 2 day drying operation. The temperature variations in bales such as noted above depends on the initial moisture content of the bales, the amount of air passing through the hay, the amount of time of fan operation and the atmospheric temperature and relative humidity.

Although the moisture content of the hay bales is a principle index to determine the completion of drying, actual measurements of the temperature is recommended as the most effective and practical method to determine the completion of the drying process. The end of the drying procedure can be determined by comparing the temperature in the hay bales with the temperature of the atmospheric temperature. When the temperature of the hay bales near the surface is balanced with the atmospheric temperature and sometimes even drops below it, the drying process is considered to have been finished. A similar conclusion was obtained by the author in long hay drying with a barn hay drier.

Summary

The results reported in these tests cannot be considered as conclusions but only as limited observations. Further investigations are required to substantiate or modify them. Some of the major points observed in these tests are as follows :

1. The over-all performance of a slatted-floor installation with a supplementary heating unit used for drying baled hay was found to be reasonably satisfactory in the experimental trials.

2. Use of blanking plates had a significant effect on raising the temperature and reducing the relative humidity of the entering air.

3. By use of supplemental heat the temperature of the entering air increases by 3-4 degree C and the relative humidity of the entering air decreases by 4-10% which resulted in reducing the time required to dry the hay bales.

4. Continuous observations of the moisture content of bales at 9th tier shows a hay-damping process at the beginning of the drying which is normally encountered in drying long hay.

5. Horizontal and vertical distributions of moisture content in bales

varies as was the case in drying long hay, and they can be used as an index to predict the over-all process of drying of hay bales.

6. Temperature variations in bales are similar to that of long hay in the drying process and actual measurements of temperature of bales near the top tier is recommended as the most effective and practical method to determine the completion of the-drying process.

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