To the Graduate Council:

I am submitting herewith a thesis written by Donald Dan Eller entitled "Evaluation of Solar Hay Drying and Collector Efficiency." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agricultural Mechanization.

Zachary A. Henry

Z. A. Henry, Major Professor

We have read this thesis and recommend its acceptance:

John D. Sewell

B. L. Bledsoe

John H Reynolds

Accepted for the Council:

L. Evans Roth

Vice Chancellor
Graduate Studies and Research

EVALUATION OF SOLAR HAY DRYING AND COLLECTOR EFFICIENCY

A Thesis
Presented for the
Master of Science
Degree
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Donald Dan Eller

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ABSTRACT

Two solar collectors were constructed and adapted for hay drying. Instrumentation was adapted to obtain data adequate for collector and drying efficiency.

A south facing metal barn roof (3.90 m by 12.19 m) was adapted for solar collection by placing plywood under the rafters, forming 55.88 cm by 10.16 cm ducts. A comparison was made between a black painted and a badly weathered surface. In addition, a 1.52 m by 18.29 m suspended plate collector was constructed so that the heated air was paralleled into the same drying system, so that it could be used with or separated from the roof collector. The open construction drying chamber was sufficient for five 500 kg roll bales.

Instrumentation and measurement was provided for temperature, relative humidity, air velocity, system air pressure and solar radiation, along with periodic hay moisture content values. A special lithium chloride, heated electrical hygrometer was designed, constructed and calibrated which was used to determine drying conditions of the air within the large bale.

Drying experiments conducted in late fall, 1976, showed that, even under the adverse conditions of very low seasonal temperatures and high relative humidities, the solar collectors increased drying potential of the air adequate for moisture removal from the hay bale.

Solar collector efficiencies compared favorably to those obtained by earlier researchers, with efficiencies of 65.5 percent for the suspended-plate collector and 45.4 percent for the roof collector. In addition, an increased efficiency of 5.8 percent was found for the painted roof as compared to the weathered roof.

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INTRODUCTION

I. BACKGROUND

The increased cost of feed concentrates for dairy and beef cattle has brought about a need for more high quality forages. One way to increase the amount of high quality forages is to utilize barn drying of high moisture hay. Barn drying lowers the loss of leaves which contain a higher percentage of nutrients than any other part of the plant. Barn drying also extends the hay producing season to include those times when field drying is not possible. This is especially important in early spring haying when there is increased danger of weather damage existing.

Cost of energy has caused a decline in barn drying. Solar energy has been used extensively in grain drying and could be a partial solution to the hay drying problem; however, research on solar energy for barn drying has been limited. Weaver and Wylie (1939) stated that solar heat for barn drying hay as compared with artificial-heat drying provided a 90 percent reduction in dryer investment, a 75 percent reduction in power requirements, and resulted in higher quality hay than field drying.

Labor cost has made mechanization of haying methods necessary and has resulted in the trend toward large hay packages, such as high-density roll bales and large stacks. The need for higher quality forages has increased the necessity of drying these large hay packages in a barn system. Lower cost solar energy systems would make this more feasible.

II. OBJECTIVES

Complete evaluation of a solar drying system and development of all needed instrumentation systems are much greater tasks than could be accomplished in the allocated time of this research effort. The purpose of this investigation was to test the feasibility of solar energy for drying large hay bales. A further purpose was to evaluate a metal barn roof as a collector and compare its performance with a free-standing suspended-plate collector.

The specific objectives were:

1. To evaluate the use of solar energy for drying of large package round bales.
2. To compare the efficiency of a roof collector to a free-standing, suspended-plate collector.
3. To develop an instrumentation system adequate to accomplish the above objectives.

CHAPTER II

REVIEW OF LITERATURE

I. SOLAR ENERGY AND LOW TEMPERATURE DRYING

The recent energy crisis has forced an awareness upon the agricultural and industrial communities that energy is a valuable resource which must be efficiently and conservatively used. In the past the primary emphasis of agricultural technology was to increase yields and mechanise crop production. It is now evident that additional emphasis must be placed upon alternative energy sources along with more efficient energy processes.

Bowers _et al_.(1975) stated that solar energy is a readily available, alternative energy source which can be used in the curing and drying of farm crops. The daily and seasonal energy variation, along with the collection and utilization equipment cost for solar energy, have, in the past, slowed development of this alternative energy source. Today's energy situation demands that the utilization of every possible energy source be investigated, including solar energy.

The seasonal demand for solar energy, along with a low load factor on the collection devices, makes solar energy utilization even more important in agriculture than in other industry or domestic applications (Pelletier, 1959). Bailey and Williamson (1965) stated that the use of a solar air heater for supplying warm air to a relatively sophisticated drier offers marked advantages over open-air drying even though a certain amount of mechanical sophistication is introduced. In an air preheating arrangement, solar energy would provide a definite fuel savings as a supplemental energy source for the curing and drying of crops.

Bauman et al. (1975), in one of the more recent investigations using solar energy for grain drying, applied solar energy to corn drying by converting the roof of a metal barn into a solar collector. They placed a false bottom under the roof rafters at a total expense of $465.12 for the system. It was estimated that the equivalent of 5752 KWH of solar heat was collected from the metal roof for one curing season. At 2.55 cents per KWH, this represented a savings of $146.68, which was 32 percent of the modification cost.

A committee in 1977 studied the use of solar heated air in grain drying and provided an overall view of simulation studies at five locations in Kansas, Minnesota, Ohio, and Indiana. They stated that solar heat appeared more feasible than natural (ambient) air drying east of the Mississippi River because of more humid natural air condition. For example, in Indianapolis, based on 10 years of weather data, a solar collector with 50 percent efficiency using 23.2 cm^2 of collector per bushel of corn reduced air flow requirements more than 50 percent. An air flow of 0.07 m^3 per minute per bushel dried corn, which started at 24 percent moisture content on October 15, to safe storage in all ten years of study. However, their report stated that studies in Minnesota, where weather was cooler and drier, showed that slightly over 10 percent more natural air flow replaced the solar heated air system (Pratt, 1977).

Future energy shortages and increases in cost of conventional energy will increase the importance of development of other low-temperature solar drying systems for many agricultural crops. This means more technology must be oriented in this area than has been in the past.

II. LOW-TEMPERATURE SOLAR COLLECTORS

Baird and Bagnall (1975) stated that, since a wide range of materials and configurations can be used to collect solar energy sufficiently for crop drying, the challenge comes in designing a collector that shows promise of becoming economically feasible. Solar collectors were divided into three general categories: (1) the collector is the crop itself; (2) collectors which heat water, and then heat air through the use of a water-to-air heat exchanger; and (3) collectors in which air is heated directly. The first category requires equipment for exposing the crop to the necessary amount of solar radiation. Also, some crops are poor solar absorbers. The second category has a high initial collector cost which might be partially offset by increased performance characteristics and by energy storage capability. Baird and Bagnall (1975) also stated that the direct-heated-air collector showed the most promise, primarily due to its simplicity and low initial cost. They stressed that two main functions of a solar air heater were to absorb the solar radiation and transfer the absorbed heat to the air. The major problem is associated with the second function since almost any material can be modified to absorb a high percent of the insolation. They reported that a flat-plate configuration performs very well as an absorber, but poorly as a heat exchanger since the surface area is minimum and the air flow is quite often laminar while moving over the plate.

Buelow (1962) stated that a basic solar energy collector for crop-drying applications was a metal roof collector coated with a good absorber finish. He reported that an air flow rate of 3.05 to 4.57 m^3 per minute per m^2 of collector area with a 9.21-cm passage between top and bottom of a south-facing collector inclined at an angle for maximum exposure provided an air temperature rise of 5.56 to 8.33°C on a clear day.

Sobel and Buelow (1963) reported the effectiveness of steel roofing materials (bare-plate collectors) under which air was moved in rectangular ducts to remove the collected heat. They obtained best results with newly painted, weathered, and weathered-painted surfaces (as compared with galvanized) with corrugations perpendicular to air flow through 7.62 to 10.16 cm depth air ducts. Collector efficiencies of 42 percent were reported with an air flow of 3.05 m^3 per minute per m^2 of collector surface through the ducts.

Buelow and Boyd (1957) found that a flat black sheet suspended between an insulated surface and a glass cover (suspended-plate collector) could heat air being circulated on both sides of the black sheet with an efficiency of 80 percent where the temperature rise was 11.1°C. Higher temperature increases could be obtained but with decreasing efficiencies.

III. HAY DRYING

Ensminger (1970) mentioned two forms of hay drying systems which are used with hay harvested at 30 to 35 percent moisture content: batch or platform dryers and wagon dryers. Batch dryers consist of stationary slotted platforms on which the hay is placed while drying is effected by forcing air (heated or ambient) through the forage. Wagon dryers, essentially batch dryers on wheels, were developed to reduce the high labor requirements of batch drying. Some wagons are covered with a nonporous material under which heated air is forced, and others are open and used in a drying shed. He listed three factors which affected variable cost of drying: (1) the initial moisture content of the forage, (2) the cost of energy, and (3) temperature rise required to raise the air to 60°C. The cost of drying hay to 15 percent moisture content from 30 percent was shown to be one-fourth the cost to dry from 40 percent.

Heath _et al_. (1973) listed the following factors affecting hay quality: (1) the growth stage and time of harvesting, (2) first or subsequent cuttings, (3) leaf content, (4) damage to forage, (5) physical form in which it is fed, and (6) species. Contributing effects are drying method and drying time. Final leaf content is greatly dependent on the harvesting and drying method because leaves are lost in haying at a higher percentage than the stems. Drying methods such as barn drying (solar or other type) lower losses due to weather, allow forages to be harvested earlier in the season, and permit harvesting of the early growth.

IV. INSTRUMENTATION

Automation and scientific advances in agriculture have resulted in a rapid increase in need for measurement systems, many of which must be designed especially for the specific problem. In order to accomplish this, new adaptations of standard instrumentation must be found, and specialized instruments must be developed which will provide information in adequate form.

Temperature

Simpson and Pettibone (1975) described the copper constantan thermocouple; a sensing element which is resistant to corrosion in moist atmospheres, for measuring temperature in the range of this experiment.

Relative Humidity

Ross (1975) stated that no sound theoretical basis accompanied the discovery of the wet and dry bulb psychrometer for measuring humidity, but that it is probably the most commonly used device for measuring humidity today. This psychrometer is made up of two identical temperature sensors; one senses the temperature of the ambient air, and the other senses the temperature resulting from the maximum evaporative cooling permitted by the ambient conditions.

Air Pressure

Zoerb (1975) stated that measurement of pressure is one of the most frequently performed operations in the field of instrumentation. He stated that liquid manometers, Bourdon tubes or other mechanical pressure measuring elements may be used when a static pressure is being determined. Of the liquid column elements, the inclined-tube manometer is especially useful in pressure measurements because of its sensitivity.

Air Velocity

Replogle and Birth (1975) stated that the hot wire anemometer is based on the variation in resistance of an electrical conductor element with element temperature; element temperature varies with the velocity of a gas passing the element. The temperature may be held constant and the current measured, or the current may be maintained constant and the resistance of the wire measured. Thermo-Systems, Inc. (1973), described a heated-element anemometer which measures velocity by sensing the cooling effect of a moving flowstream over the heated sensor surface. Thermo-Systems, Inc. (1973), pointed out the accuracy (± 2 percent) as being an added advantage in addition to its adaptability.

Solar Radiation

The World Meteorological Organization (1965) listed several instruments for recording radiation which include pyroheliometers, pyranometers, pyrgeometers, and pyrradiometers. They described characteristics which make the pyranometer of great value in field studies for measurement of global and sky radiation. The pyranometer can function in all weather because of its durable design, and can resist corrosive effects of damp air because of the sealed glass casing. It is also suitable for field use because of its mobility. The World

Meteorological Organization (1965) recommended that the pyranometer be inspected once per day when in use.

V. ELECTRICALLY HEATED HYGROMETER

Many methods are listed for the measurement of psychrometric conditions by scientists such as Ross (1975), but none are satisfactory for the measurement inside large hay packages. However, many researchers such as Baxter (1951), Hedlin and Trofimenkoff (1965), and Nelson and Amdur (1965) have used a modified electrically heated hygrometer to obtain a measurement of dew point temperature in a wide variety of restrictive conditions.

Hedlin and Trofimenkoff (1965) described a lithium chloride heated electrical hygrometer with the following features. It can be used over a wide range of humidity; the results are given in terms of temperature which can easily be converted to dew point temperature; and little maintenance is required. The hygrometer is basically a bifilar winding of a noncorrosive metal on an insulated core coated with a lithium chloride (a hygroscopic salt) treated fiber. Foxboro (no date), Baxter (1951), and Hedlin and Trofimenkoff (1965) all used a glass-fiber tape saturated with a lithium chloride solution. All used silver wire with the exception of Foxboro who used gold. A 24 or 25 volt alternating power source was connected across the bifilar windings in all of the above cases. Baxter (1951), and Hedlin and Trofimenkoff (1965) placed a thermocouple in the hollow center of the core to measure the element temperature.

Hedlin and Trofimenkoff (1965), Baxter (1951), and Foxboro (no date) stated that the temperature of the salt film on the hygrometer was regulated so that the vapor pressure of the contained water equaled the water vapor pressure in the surrounding air. The resistance of the lithium chloride film varied according to the exchange of moisture with the surrounding air. Nelson and Amdur (1965) explained that when a salt crystal is exposed to water vapor at a relative humidity below that of its phase transition, the electrical resistance of its surface will be very high. As relative humidity increases to that corresponding to the initiation of a liquid phase on the surface of the crystal, the electrical resistance will decrease rapidly. They also stated that concentration of the lithium chloride treating solution may be varied over wide limits, and the amount of solution applied will vary somewhat with the application method.

Foxboro (no date) stated that the hygrometer could be used in ambient temperatures of -45°C to 104°C with an air velocity under 15 m per minute. Baxter (1951) stated that the hygrometer operates satisfactorily in a range of ambient temperatures of -18°C to 104°C, even in air which contains a large amount of foreign matter.

Nelson and Amdur (1965) concluded that the electrically heated hygrometer is a very precise instrument (± 0.15°C) when suitable care is taken in the installation. The regions of highest percision are between -12°C and +34°C, and above 41°C dew point. In regions of phase ambiguity, the errors introduced must be considered. For many uses the errors introduced by ignoring this ambiguity do not affect the usefulness of this instrument, considering the simplicity and relatively low cost of such installations.

CHAPTER III

DRYING FACILITY

The two types of structures chosen to collect available solar energy were: (1) the shed metal roof of an existing barn, and (2) a free-standing suspended-plate collector constructed near the barn. The shed roof (3.90 m by 12.19 m) faced 27 degrees east of south at 36 degrees latitude and was inclined approximately 16 degrees from the horizontal. It had an effective collector area of 47.56 m^2. Plywood was placed on the lower side of the rafters to form 20 ducts 55.88 cm by 10.16 cm which emptied into a manifold header duct. The header duct (Figure 1) serving the roof collector had a continuously increasing cross-sectional area (from the ends of the barn toward the center) to maintain more uniform air velocity. Half of the roof surface was painted black and half left in a badly weathered condition to evaluate the effect of surface finish on the collector effectiveness.

The free-standing suspended-plate collector (1.52 m by 18.29 m with total area of 27.87 m^2) used a collector surface of black, 6-mil polyethylene. The glazing (top cover) was 6-mil clear plastic, and the duct below the collector surface was formed by 0.95 cm plywood (Figure 2). Air moving above and below the absorber surface removed the collected heat. The collector faced due south and was inclined 28 degrees from the horizontal for optimum collection of solar energy as determined from plots of mean daily solar intensity as a function of

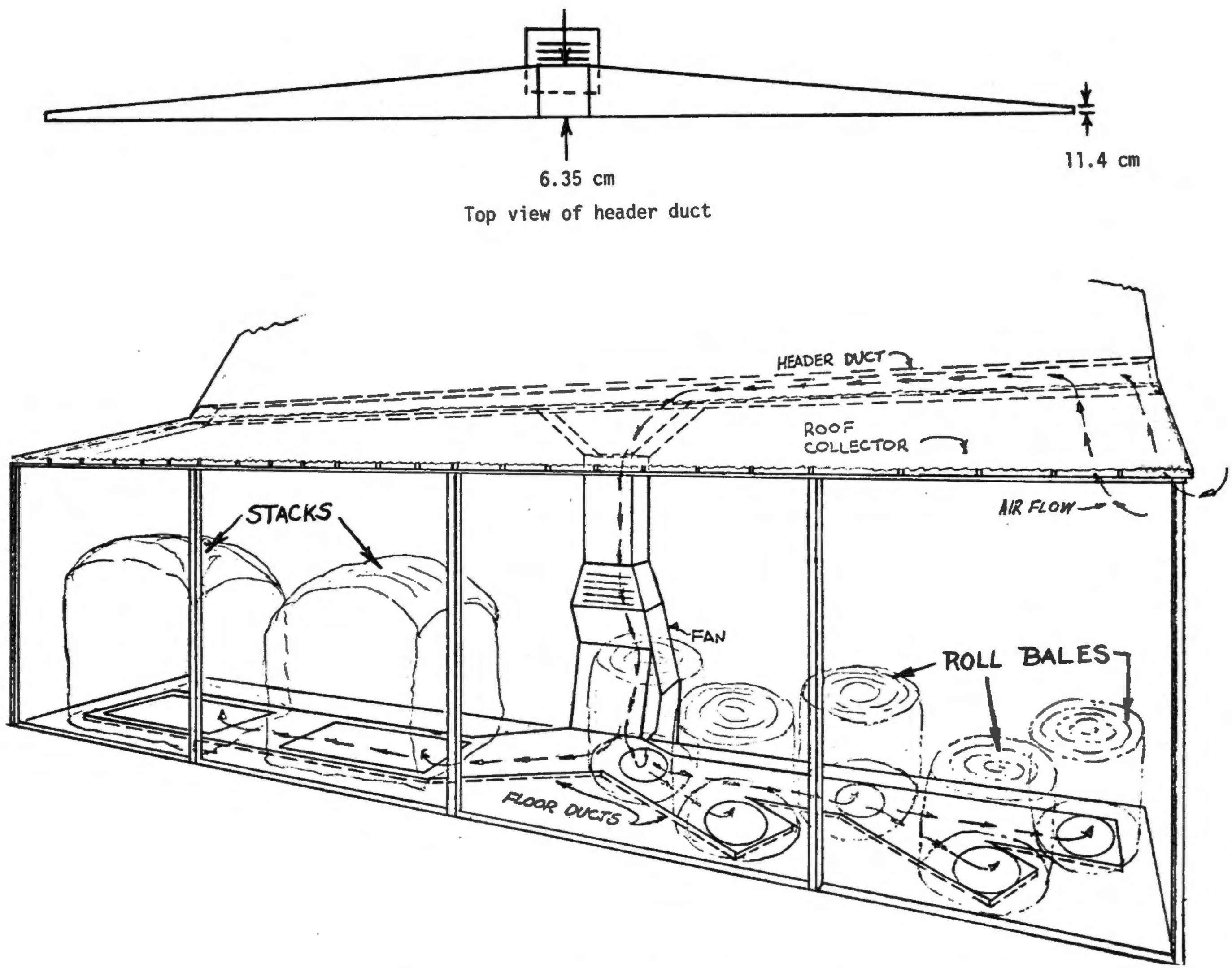

FIGURE 1. Details of drying chamber with top view of header duct above.

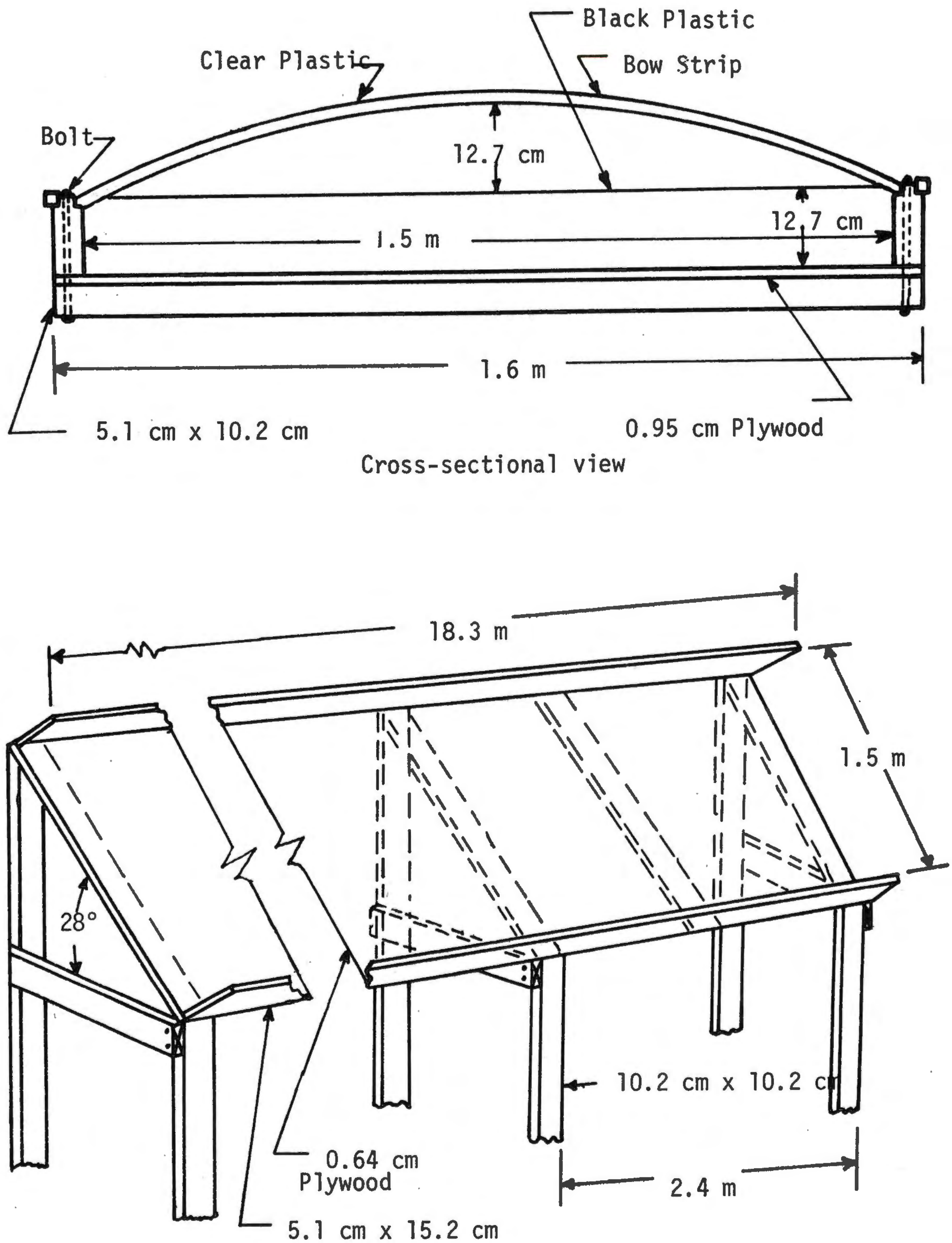

FIGURE 2. Free-standing suspended-plate collector: above, cross-sectional view showing upper and lower passage for air; below, base support for collector.

inclination angle (ASHRAE, 1972). Flow of heated air to the dryer system fan was through a 45.72 cm inside diameter, wire reinforced tubular duct. Two shut-off valves were used, one in the roof down duct and another in the duct from the free-standing collector. This allowed the use of both collectors together or either one individually.

The drying chamber (Figure 1) was designed to accommodate both low density stacks and low or high density roll bales. It had a capacity of five rolls and two stacks (about 5.44 metric tons) of hay simultaneously. It was open construction to allow high moisture air exiting from the hay packages to readily escape to the atmosphere. A 45.72 cm diameter tube-axle fan capable of delivering 105 m^3 per minute of air at 6.35 cm of water static pressure was powered by a three horsepower motor. The system was designed for a minimum flow rate of 15.10 m^3 per minute of air per metric ton of hay (Hall, 1957). The floor ducts were designed for one square meter cross sectional area for each 305 m^3 per minute of air flow (Bledsoe and Henry, 1976).

CHAPTER IV

INSTRUMENTATION

I. PSYCHROMETRIC MEASUREMENT INSIDE THE BALE

The lithium chloride electrically heated hygrometer was selected as the type of sensing device for the psychrometric properties of the drying air within the large hay packages because of its adaptability to operate under the adverse conditions. A sensing element and appropriate tubular shield were designed, constructed and calibrated. A 0.635-cm o.d. nylon rod, 7.62-cm long, was double threaded to hold the bifilar winding (electrodes) in place without contact (Figure 3). The threads were 0.0508 cm deep with 15 turns per 2.54 cm and were covered with a very thin nylon mesh before being wound with 0.0254-cm diameter silver wire (Figure 4). The wires were anchored at one end by insertion into two small radial holes. The other ends of the wires were inserted through two longitudinal holes in a collar which held the core in place inside the tubular shield. These two ends were then connected to leads from a 10 v alternating power source. The element, after being wound, was saturated with a 3.54 molar solution of lithium chloride. A small longitudinal hole was made in the center of the element into which a thermocouple was placed. Figure 5 shows the element in position to be inserted into the protective shield with the thermocouple and leads exposed. The leads from the thermocouple and bifilar windings extended

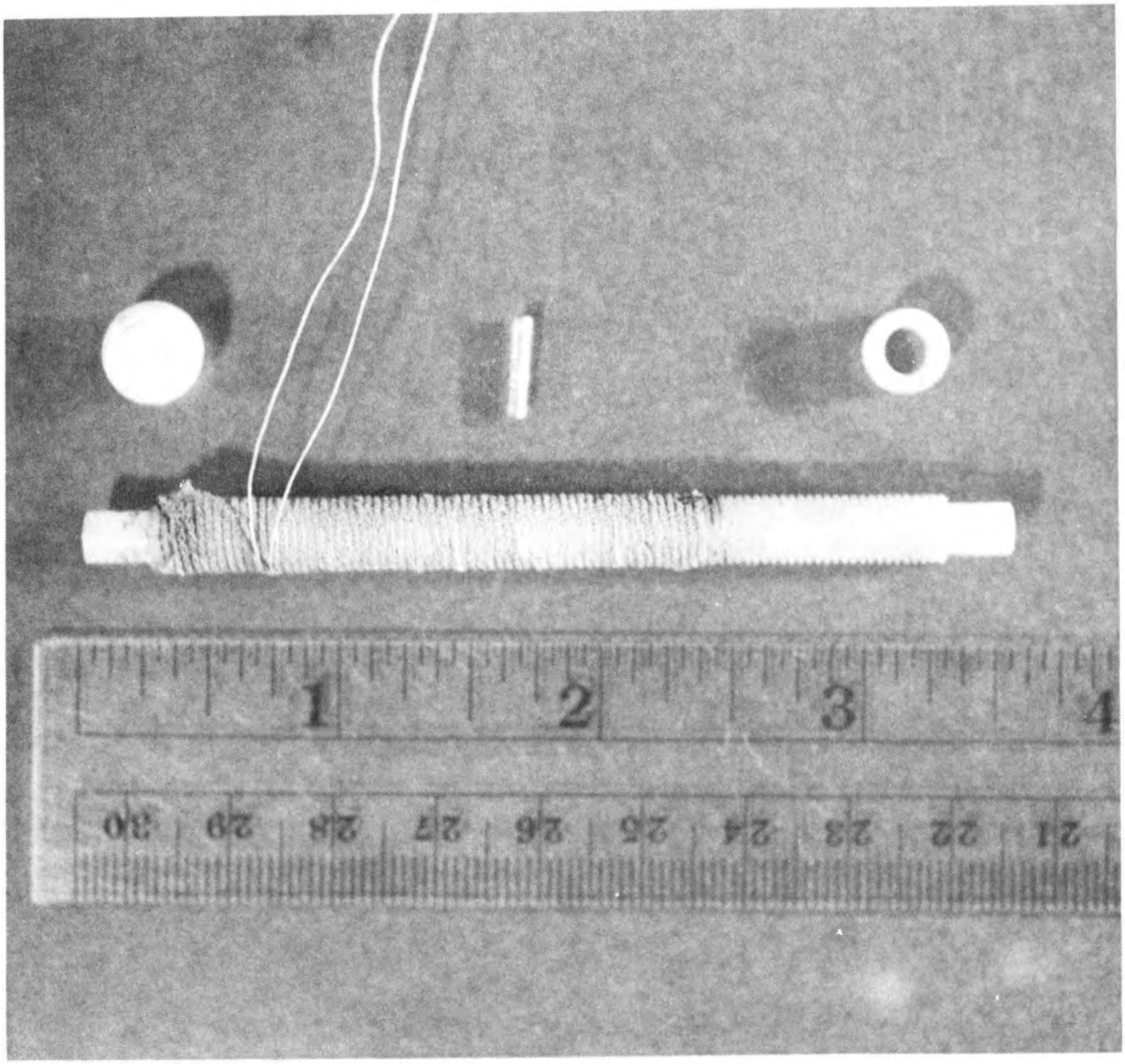

FIGURE 3. The threaded nylon core of the hygrometer showing the conical tip, the metal pin for securing the tip, and the nylon collar for holding the core in place inside the tubular shield.

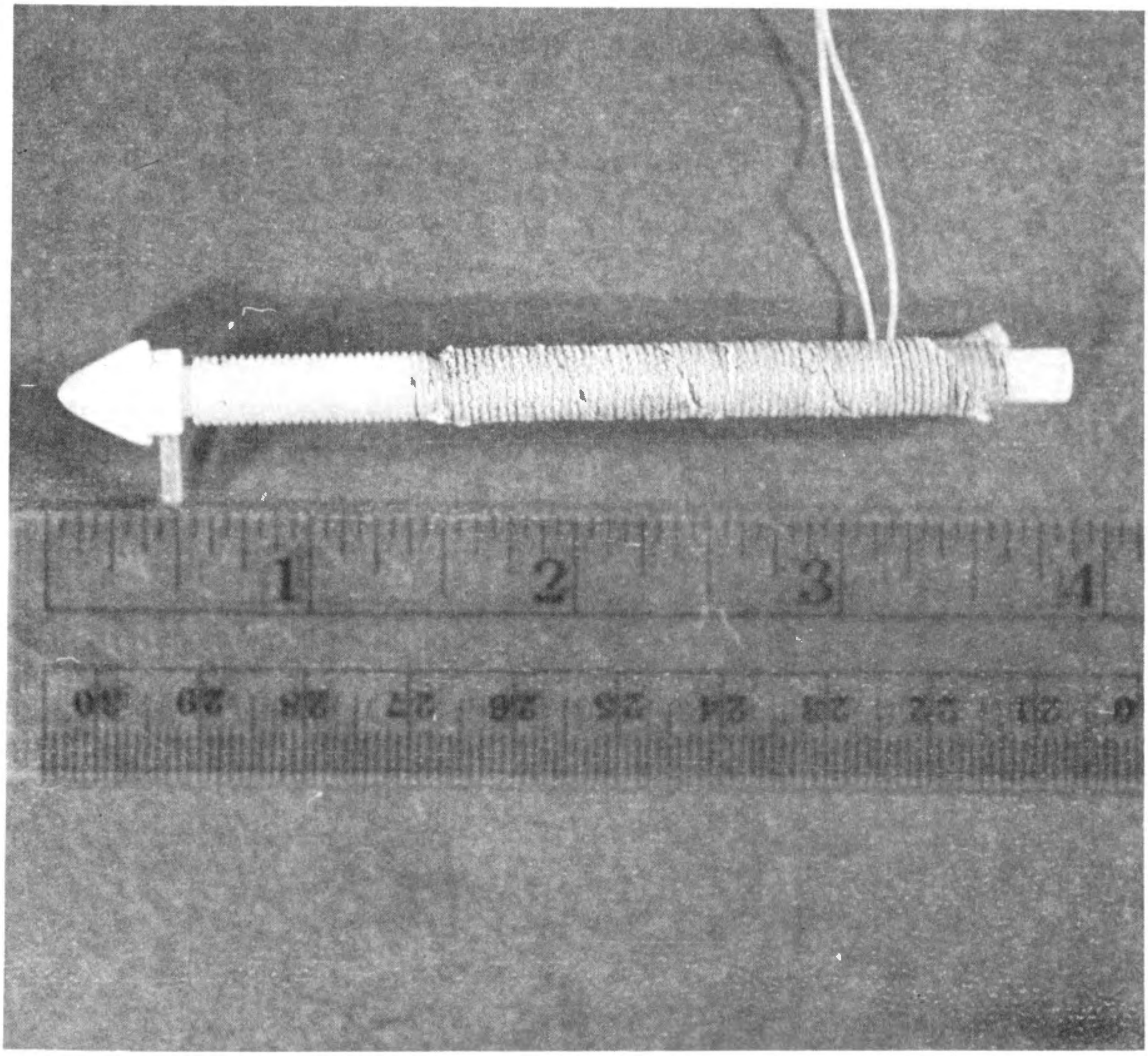

FIGURE 4. Hygrometer element showing nylon fiber cover and bifilar winds.

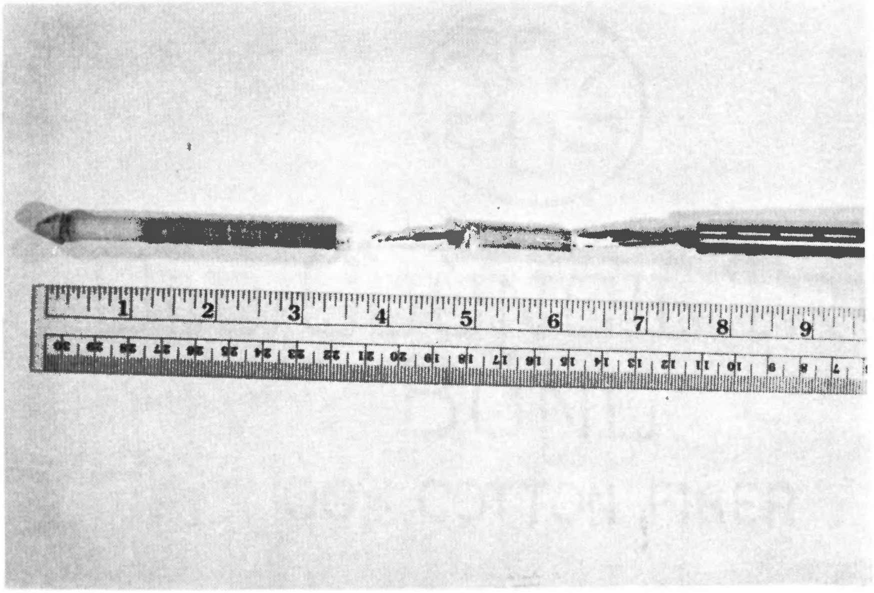

FIGURE 5. The hygrometer element, thermocouple and leads in position to be inserted into the metal protective tube.

through the protective tube to a recorder and power source, respectively.

The prepared element was enclosed in the end of a 0.95-cm i.d. metal tube of adequate length to pierce into the greatest depths of the large hay bales (Figure 6). The end of the tube which covered the sensing element was ventilated with 0.17-cm holes for free movement of air around the element. Additional protection was provided by a gauze sock which was placed over the end of the probe to prevent foreign matter from coming into contact with the element. This permitted the element to be inserted into the hay bale with maximum protection and thus permitted a greater freedom in selection of the position of measurement within the bale.

Seven hygrometer elements and protective tube assemblies were constructed and calibrated individually in a controlled environmental chamber in the range of temperatures and relative humidities expected for the drying hay. The chamber and hygrometers were allowed to come to equilibrium at each state point before a calibration reading was taken. The hygrometer reached equilibrium with the chamber almost as fast as the chamber could adjust to a new state point when adjustments were made in steps of not more than 2°C. Fifty calibration points for each element were taken before the experiment and forty after the experiment. Calibration was made by plotting element temperature against dew point. Table 1 lists the pre-use, post-use and the combined correlation coefficients for the calibration of each element. Elements 3, 4, 5, and 6 were used in all tests. Element 1 was used in the first two tests and replaced by Element 7 for the third test. The calibration curves

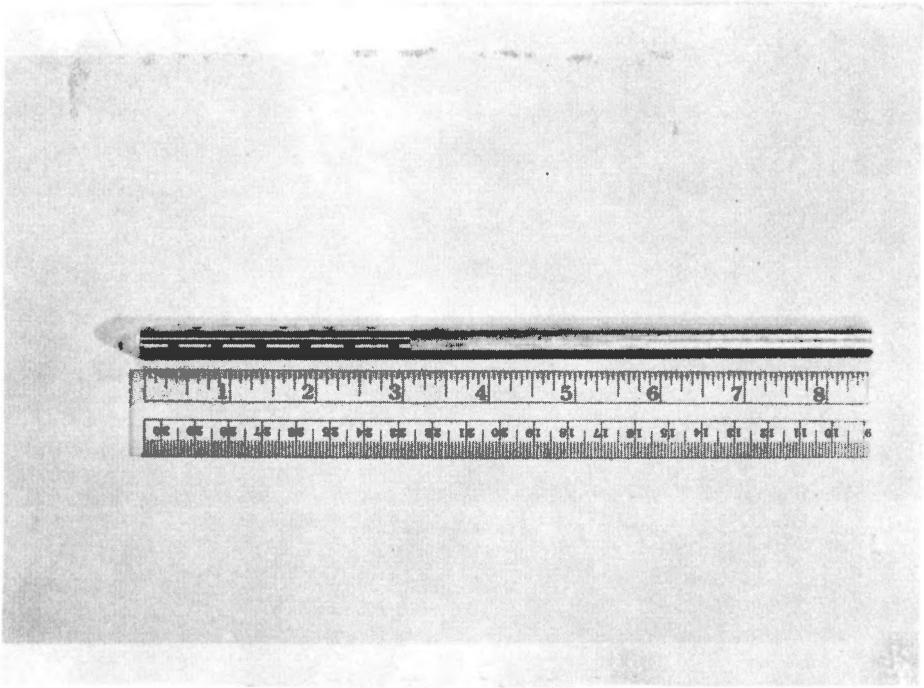

FIGURE 6. Hygrometer element in protective tube, showing the conical tip of the element and the ventilation holes.

TABLE 1. Correlation coefficients for the calibration curves for pre-use, post-use and combined pre-use and post-use for each hygrometer element.

Element	Pre-use			Post-use			Pre-use and Post-use		
	Correlation	Slope	Intercept	Correlation	Slope	Intercept	Correlation	Slope	Intercept
1	0.9388	1.0751	18.467	0.9806	1.0357	6.527	0.7869	1.0801	12.564
2	0.9625	1.1349	13.677	0.9885	1.1619	13.221	0.9758	1.1482	13.430
3	0.9338	1.2340	19.891	0.9901	1.1307	8.762	0.7985	1.2080	14.438
4	0.7085	0.7972	32.066	0.9675	1.1676	17.431	0.8193	0.9963	24.5195
5	0.9764	1.1339	10.486	0.9868	1.0387	6.752	0.9321	1.0973	8.097
6	0.9707	1.1754	12.882	0.9854	1.0784	8.906	0.9290	1.138	11.138
7	0.9645	1.1589	15.121	0.9946	1.2078	11.855	0.9760	1.1877	13.462

Elements 5 and 7 are shown in Figures 7 and 8, respectively. Both Table 1 and Figures 7 and 8 show that the calibration shifted after use. Figure 7 represents an element with minimum shift, and Figure 8 represents an element of maximum shift. Close examination of each element and protective rod after the experiment indicated that the shift was a result of moisture collecting in the rod and running down onto the element. The protection of the element from physical damage of foreign matter while in the hay bale was adequate. No resultant effect on the element was evident. Psychrometric data for the inside of the bale were obtained from the curve of the combined calibration points before and after use in the hay bales.

II. SYSTEM MEASUREMENTS AND DATA COLLECTION

Temperature and Humidity

Temperatures were all obtained from copper constantan thermocouples. For each wet bulb thermocouple, a wick extended through a tube secured into the base of a plastic bottle. Two separate wet bulb temperatures were obtained from each desired position to minimize the danger of incorrect readings. Wet and dry bulb temperatures were obtained at the following locations: (1) ambient at one location outside the barn and near the fan inside the barn; (2) in the transition at the outlet end of the suspended-plate collector; (3) in the roof down duct at the header duct exit; (4) at the end of the duct from the suspended-plate collector near the system fan; (5) in the mixing chamber at the bottom of the down duct; and (6) at the inlet and outlet of the system fan. Dry bulb temperatures only, were obtained inside the rafter

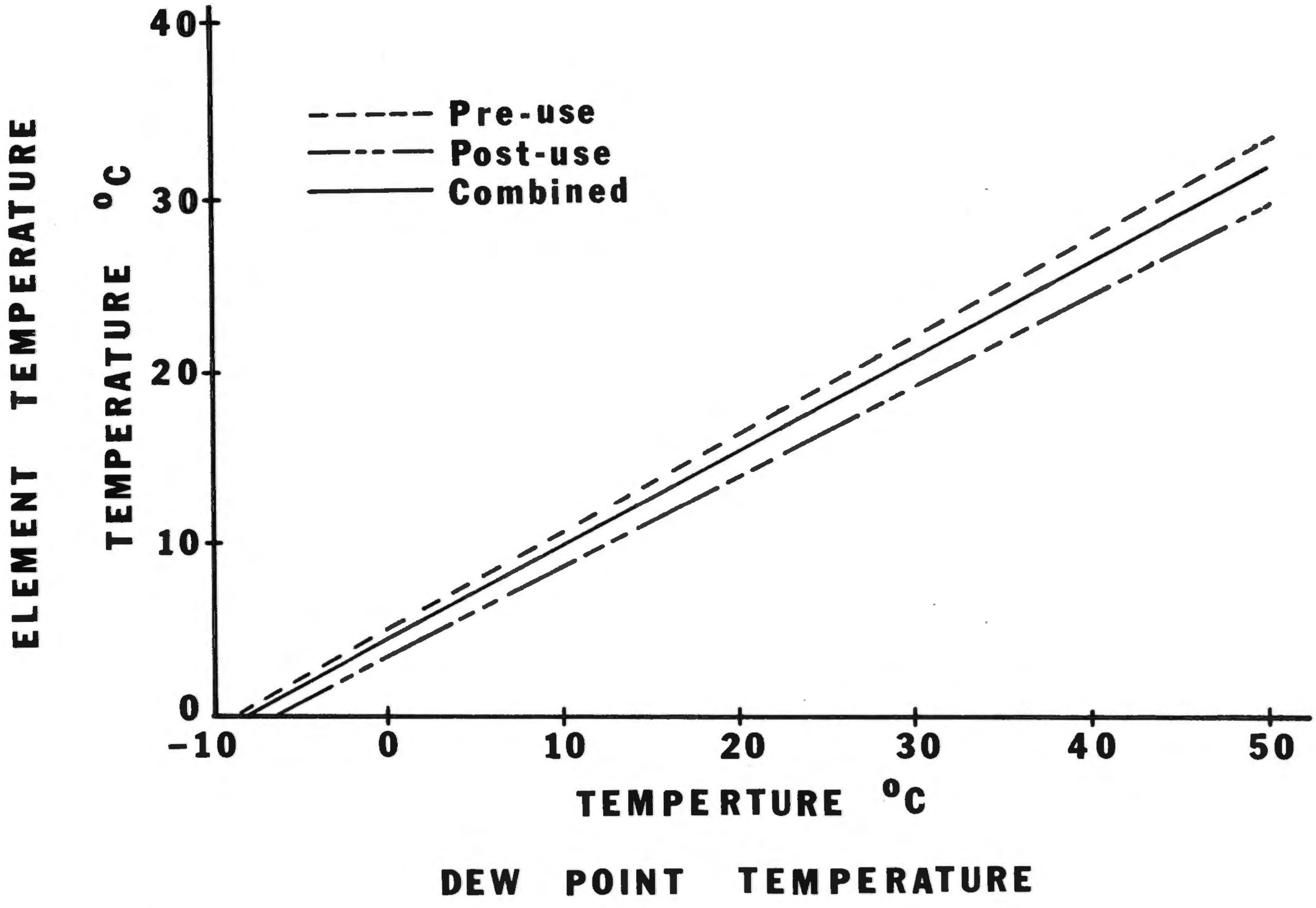

FIGURE 7. Calibration curve of Element 5 which showed a minimum shift after the experiment.

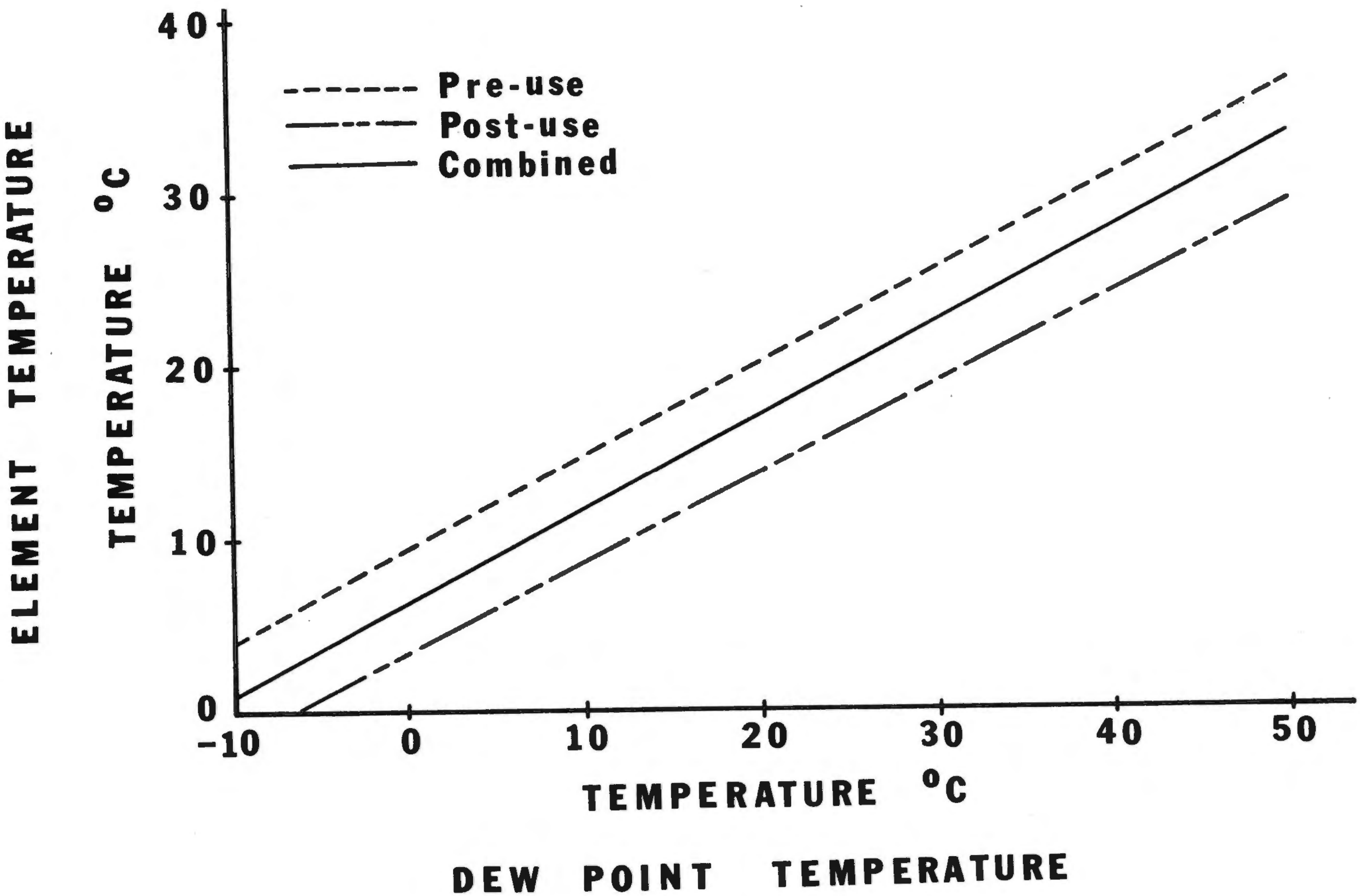

FIGURE 8. Calibration curve of Element 1 which showed a maximum shift after the experiment.

ducts just before the header duct and at the top, center and bottom of the drying hay bale, along with the temperature of the hygrometer element. A digital acquisition system was provided for recording all temperatures and for recording instantaneous solar radiation as discussed below. The data recorded included time, date and element position number.

Solar Radiation

Solar radiation was obtained from an Eppley Model 50 (Eppley Laboratory, Inc., 1960) pyranometer mounted away from any objects which might cause interference. A periodic digital recording was made of the potentiometric output along with a continuous strip chart recording.

Air Velocity and Static Pressure

Air velocity measurements were made with a hot wire anemometer coupled to a digital volt-meter and were obtained at the following locations: (1) in the transition at the outlet end of the suspended-plate collector, (2) inside the cylindrical duct from the suspended-plate collector, (3) between each rafter duct, (4) in the down duct from the roof collector, and (6) at the inlet and outlet of the system fan. Static pressure measurements were obtained from the same locations and at the same times as the velocity measurements with a static pressure tube and inclined manometer.

CHAPTER V

PROCEDURE

I. GENERAL EXPERIMENTAL DESCRIPTION

Three tests, each of which included five high-density, high-moisture roll bales of late fescue growth, were dried on the following dates in the fall of 1976: (1) November 4-6; (2) November 9-13; and (3) November 18-24 and November 30 to December 3. Labor availability and inclement weather caused the experiment to be interrupted during the third test. Stacks were not used in this experiment; therefore, the duct to this area of the drying chamber was blocked. The location of the roll bales in the drying chamber is shown in Figure 2, page 14. Low ambient temperatures during the tests required that heated air from both solar collectors be used simultaneously to acquire adequate temperature rise. Instrumentation, as previously described, permitted air properties and collector efficiencies to be determined separately for each collector. Each bale was weighed before and after drying to determine the amount of moisture loss during the drying period.

II. DATA COLLECTION

Velocity, Pressure, Psychrometric Data, and Solar Radiation

Temperatures, relative humidities, and bale internal psychrometric conditions were recorded as previously described. All were recorded for all three tests hourly during night and day until November 22. After November 22, the system fan was turned off from 1600 hours to 1800 hours the following day; this resulted in no data during the periods when the fan was off with the exception of ambient temperature and relative humidity. A complete set of air velocity and pressure data were obtained on November 11, 19, and 23 to represent the conditions for the second and third drying tests. Air velocity and pressure data were not obtained for test one. An additional check of the data at selected locations was made on November 18. Solar radiation was recorded as previously described. Solar radiation data were recorded continuously from November 6 through the remainder of Test 1 and the two following tests.

Hygrometer Placement in the Bale

The heated-element hygrometer was placed in the bale by first boring a hole to the center with a 2.54-cm core sampling tool. A 1.90-cm pipe was then placed in the bale and the hygrometer element, mounted in the protective rod covered with a gauze sock, inserted in the 1.90-cm pipe. The 1.90-cm pipe was then removed, leaving the element in place in the center of the bale. The thermocouple which measured the dry bulb temperature in the center of the bale was inserted in the same manner so that it would be located approximately 5 cm from the hygrometer.

Moisture Sampling

Core samples for moisture content were taken daily during all drying periods for each test at 0800, 1200, 1600 and 2000 hours with the exception of test three after November 22, when the 2000 hour sample was omitted. Subsamples were taken from the top, center and bottom of each bale and combined before oven drying to obtain wet-basis moisture content.

III. DATA EVALUATION

Temperatures of the ambient, heated and internal (top, center and bottom of the bale) air along with relative humidity of ambient, heated and center of the bale air were compared to obtain an indication of the drying action in each bale. All were plotted on the same graph for each bale of each test. The vapor pressures of the air inside the hay bales were compared with the ambient and heated air. Vapor pressures of ambient, heated and internal bale air were used with the previously mentioned temperatures and relative humidities to determine moisture removal.

Removal of moisture from the hay bale, as determined from the core samples, was compared for selected periods with the air moisture content entering and leaving the bales. A four hour period (1200 hours to 1600 hours of November 6) for Bale 5 of Run 1 was arbitrarily selected to evaluate the moisture removed from the hay. Wet and dry bulb temperatures of heated air along with dry bulb and dew point temperatures for bale internal conditions were used with air volume flow rate data to obtain total moisture removal for the four hour period. The difference in heated air and internal air moisture ratios was obtained, and this difference was multiplied by total volume of air forced through the hay bale in the given time period to produce the total moisture removal value.

Collector efficiencies were determined by comparison of the available solar radiation as determined from the daily average pyranometer measurement with the heat collected by the air as it passed through the collector. The method of calculation of the efficiencies is shown in Appendix C.

CHAPTER VI

RESULTS

I. SOLAR HAY DRYING

The adverse conditions of late fall weather affected the experiment, not only with respect to deviation from optimum drying conditions, but also with respect to data collection. Tests one and two provided excellent temperature and insolation data for late fall conditions, along with excellent data for internal hay bale conditions. The data from test three were not as good because of inclement weather and especially, because freezing temperatures affected the wet bulb measurements. Therefore, only limited data are presented from the third test. Bales 4 and 5 of test one and Bale 4 of test two were used as representatives of each test.

Ambient and heated air relative humidities reached a difference of as much as 30 percent when the spread of ambient and heated air temperatures reached a maximum (Figures 9 to 11, Appendix A). A spread in ambient and heated air temperatures in the range of 16°C occurred at various times through the second test (Figure 11, Appendix A). However, the temperature difference of heated air and ambient air never exceeded 4°C in the first test (Figures 9 and 10, Appendix A). The increase in vapor pressure at the center of the bale (Figures 12 to 14, Appendix A) coincided with the time of highest temperature and lowest relative humidity of the drying air (time of greatest drying potential).

The heated and ambient vapor pressures remained very close with the slight variation being due to moisture variations in the air system and measurement error.

Each of the bale internal relative humidity curves for the three representative bales shown in Figures 9 to 11 (Appendix A) provides a different perspective of moisture removal from the hay bale. The bale center relative humidity for Bale 5 of test one (Figure 9, Appendix A) started at 85 percent and declined throughout the cure with the exception of an increase from 0600 to 1000 hours on November 6. The increase occurred at the point when heated air temperature took a sudden rise which explained the higher rate of moisture removal as indicated by the increased vapor pressure at the center of the bale. After the sudden rise in relative humidity, it began to drop because of an equilibrium effect after the initial impact of an increased moisture removal. Figure 10 (Appendix A) represents Bale 4 of test one whose relative humidity remained constant (around 83 percent) for the first 22 hours when it suddenly rose (93 percent range). It remained at the 93 percent level for 19 hours at which time it dropped to the 86 percent level. The rise occurred at a time of increased moisture removal because of a rise in heated air temperature and a drop in heated air relative humidity. The time period when the relative humidity was higher inside the bale extended through a period of very low temperatures, and this resulted in adequate heated air humidity data during that period to draw definite conclusions. Figure 11 (Appendix A) represents the psychrometric properties of Bale 4 of test two. The initial relative humidity curve showed a constant relative humidity of 100 percent for the first 38 hours at which time the humidity dropped at a slow but constant rate. This was matched by a general declining vapor pressure (Figure 14, Appendix A) as the cure progressed. All data for the bales discussed showed a decline in the bale center relative humidity from the beginning of the cures to the end. This indicated a decline in hay moisture content which was substantiated by the moisture content tables (Table 6, Appendix B).

Figures 15 to 17 (Appendix A) show that during the day, when solar radiation was being received, the drying air temperature decreased as it moved through the bale. During periods of no solar radiation the temperatures shifted with the air at the center of the bale being highest and the temperature at the top of the bale remaining lowest. Thus, the heated air temperature curve was between the top and center bale temperatures. The temperature at the top of the bale was lower than ambient during most of the drying period with the effect being especially evident during the day. This, along with detectable high moisture conditions at the top of the bale by feel, indicated that evaporative cooling was occurring and moisture removed from the lower part of the bale was deposited at the top.

Data listed in Table 2 for the four-hour period selected for Bale 5 of test one were used to obtain the amount of moisture removed from a sample bale in a given period of time. By using the moisture ratio differences of heated, bale center and bale top air with an average air flow rate through the bale of 18.8 m^3 per minute, an estimated 88.49 kg of water was removed from the bottom portion of the bale in the four-hour period with at least 18.94 kg being redeposited

TABLE 2. Heated air, bale center air and bale top air data for Bale 5 of test one for a four-hour period of November 6, 1976.

	Heated Air			Bale Center Air			Bale Top Air		
Time*	Dry Bulb Temp. °C	Wet Bulb Temp. °C	Moisture Ratio kg/kg Dry Air	Dry Bulb Temp. °C	Dew Point Temp. °C	Moisture Ratio kg/kg Dry Air	Dry Bulb Temp. °C	Relative Humidity Percent	Moisture Ratio kg/kg Dry Air
1200	10.2	4.8	0.00313	7.4	5.6	0.00563	3.8	100**	0.00496
1300	12.0	5.3	0.00279	8.0	6.0	0.00579	4.3	100**	0.00514
1400	11.6	5.2	0.00287	8.4	6.1	0.00584	4.7	100**	0.00529
1500	12.9	5.8	0.00283	8.7	6.5	0.00600	5.1	100**	0.00544

*Twenty-four hour clock.

**The assumption was made that a saturation condition existed at the top of the bale as evidenced by the continual wet condition of the hay at this level.

in the bale. Thus, only 69.55 kg of water exited the bale at the top. This is supported by lower air temperatures and detectable high moisture conditions at the top of the bale as previously discussed. The 69.55 kg of water removed from the bale represented a substantial drying rate that was not totally confirmed by the bale moisture content curves which dropped very little over the four-hour period (5.3 percent for the entire cure). The system for weighing the bales did not provide data of sufficient accuracy to closely estimate the total moisture loss. However, with an estimated bale weight of 500 kg and with a 5.3 percent decline in moisture content, 26.5 kg of water was removed over the entire cure. This indicated that other factors existed in the drying mechanism of the bale, other than those measured or assumed, which affected moisture displacement. Additional data will be required in subsequent tests to provide information to adequately follow the drying front and match the moisture removal data by psychrometric measurements with that of the moisture samples.

II. COLLECTOR EFFICIENCY

The suspended-plate collector used in this research had an average efficiency of 65.5 percent (Table 3). This compared with 80 percent efficiency obtained by Buelow and Boyd (1963) using a similar collector. The roof collector had an efficiency of 45.4 percent which compared with the 42 percent efficiency obtained by Sobel and Buelow (1963) using a similar roof collector. The suspended-plate collector was 20.1 percent more efficient than the roof collector.

TABLE 3. Efficiencies of roof and suspended-plate solar collectors with available energy and collected energy values for the indicated curing days in 1976.

	Suspended-Plate					Roof				
Date	Collector Efficiency Percent	Collector Energy KWH/(m^2-day)	Collector plus Duct Efficiency Percent	Collector plus Duct Energy KWH/(m^2-day)	Available Energy KWH/(m^2-day)	Collector Efficiency Percent	Collector Energy KWH/(m^2-day)	Collector plus Duct Efficiency Percent	Collector plus Duct Energy KWH/(m^2-day)	Available Energy KWH/(m^2-day)
11-6	81.1	4.393	33.0	1.789	5.417	76.9	3.531	29.7	1.363	4.590
11-10	--	5.366	38.9	1.855	4.768	44.8	1.798	43.9	1.765	3.684
11-11	64.2	1.723	51.3	1.377	2.683	56.2	1.269	44.8	1.012	2.256
11-12	55.4	1.226	36.3	0.804	2.211	32.5	0.604	30.2	0.561	1.857
11-13	62.5	2.474	35.9	1.428	3.960	32.6	1.084	29.9	0.995	3.322
11-19	59.4	2.342	29.1	1.145	3.941	39.2	1.286	37.6	1.233	3.284
11-20	52.6	1.083	28.8	0.593	2.057	46.5	0.795	43.9	0.752	1.712
11-21	62.9	2.345	30.8	1.148	3.728	36.6	1.135	31.5	0.975	3.099
11-22	67.5	2.398	28.4	1.010	3.551	41.8	1.234	41.7	1.231	2.950
11-23	67.3	3.384	34.1	1.713	5.029	42.2	1.762	39.1	1.631	4.173
11-24	81.6	3.114	23.6	0.902	3.818	50.1	1.586	48.3	1.531	3.166
MEAN	65.5		33.7			45.4		38.2		

When efficiencies were determined for each collector plus the duct leading from each collector, the roof collector and duct combined were found to be more efficient than the suspended-plate collector and duct combined. The roof collector and duct had an efficiency of 38.2 percent, but the suspended-plate collector and duct had an efficiency of only 33.7 percent (Table 3). The lower efficiency of the suspended-plate collector and duct was accounted for by the heat loss in the uninsulated cylindrical duct above ground from the collector to the fan. This was approximately four times the relative heat loss from the roof collector to the fan.

The available solar radiation collected on a horizontal plane during the three tests ranged from 0.234 to 3.694 KWH/(m^2-day) which compared with data reported by Fribourg (1976) for a fifteen-year period with a 95 percent confidence limit with a range of values from 0.116 to 4.885 KWH/(m^2-day). The solar radiation data collected in this research was within the range reported previously from past data.

Maximum and minimum ambient temperatures (Table 4) for the same time periods used to calculate available solar energy each day in Table 3 indicated that the roof collector efficiency was higher on days of high maximum daily temperatures. This was not as apparent with the suspended-plate collector, although two of the highest efficiencies did occur on days of higher maximum temperatures. Wind velocity possibly affected collector efficiency by removing heat energy from the outer surface of the collectors. This could account for some of the efficiency variations, although no definite conclusions can be drawn because of the lack of wind velocity data.

TABLE 4. Maximum and minimum ambient temperatures for the same time periods as used to determine available solar energy in Table 3.

Date	Maximum	Minimum
11-6	12.1	0.6
11-10	17.2	10.2
11-11	10.3	0.3
11-12	3.6	0.8
11-13	4.5	-4.1
11-19	17.2	5.4
11-20	12.2	5.9
11-21	9.7	5.5
11-22	4.2	0.6
11-23	5.9	0.8
11-24	11.9	2.7

The roof was divided into two equal areas, one painted black and the other left in a badly weathered condition. Data from Table 5 show an average increase of 0.49°C with the black roof over the badly weathered roof. The efficiency of the painted side was 48.2 percent compared to 42.4 percent for the weathered side; a 5.8 percent increase in efficiency by painting the weathered roof black.

TABLE 5. Temperatures and efficiencies of a painted metal roof collector surface as compared to a badly weathered metal roof collector surface.

Date of 1976	Painted		Weathered		Temperature Difference °C
	Temperature °C	Efficiency Percent	Temperature °C	Efficiency Percent	
11-6	13.50	77.8	13.31	75.9	0.19
11-10	17.28	47.7	16.69	41.7	0.59
11-11	10.47	64.9	9.44	47.3	1.03
11-12	3.74	34.7	3.54	30.4	0.20
11-13	4.27	34.3	4.00	30.8	0.27
11-19	16.42	41.2	16.00	37.1	0.42
11-20	11.35	49.4	11.05	43.5	0.30
11-21	9.47	37.7	9.27	35.5	0.20
11-22	5.86	45.6	5.20	38.1	0.66
11-23	8.97	45.3	8.19	39.1	0.78
11-24	11.98	51.6	11.28	46.5	0.70
MEAN		48.2		42.4	0.49

CHAPTER VII

SUMMARY AND CONCLUSION

The instrumentation system for obtaining collector efficiencies and drying effectiveness included an especially designed lithium chloride coated, electrically heated hygrometer for obtaining psychrometric conditions inside the large hay packages.

Five high density roll bales were dried in three separate tests in the late fall of 1976 using the combined heat from the roof collector and the suspended-plate collector. The drying reduced the moisture content of hay in the 35 percent range by approximately 5 percentage points; however, the total drying effect for the inclement weather was not sufficient within the allowed time. Psychrometric conditions inside the bale showed that a drying front existed as the drying potential of the air increased in the daylight hours, but as air was passed through the bale during the night hours, moisture was deposited into the bale.

The overall efficiency of the metal roof collector was found to be 45.4 percent. The efficiency of a black painted roof section was 5.8 percentage points more than that of a badly weathered roof section. The efficiency of the suspended-plate collector was 65.5 percent. The cold ambient temperatures caused a severe loss of heat in the duct from the suspended-plate collector to the drying chamber causing the overall efficiency to be less than the roof collector.

The following conclusions were drawn from the results of this study:

1. Solar energy can be effective for barn drying of hay even in late fall inclement weather.
2. During the cold, damp periods when there is no solar radiation, moisture will be deposited in the bale.
3. Relative humidity inside the bale drops as hay moisture content drops.
4. The lithium chloride electrically heated hygrometer provided excellent psychrometric data for internal bale conditions.
5. The suspended-plate collector is more efficient than the metal roof collector, but either collector will supply adequate temperature rise under normal weather conditions.
6. A black metal roof is more efficient than a badly weathered metal roof.

I. RECOMMENDATIONS FOR FUTURE STUDY

The work presented here was only the first step in the evaluation of solar energy hay drying. More conclusive results must be determined from future data. Modifications needed are evident from the results obtained in this research project.

The hygrometers need modification to eliminate problems which caused large variation in some of the elements which would require a more extensive study of their performance.

An instrumentation system to record relative humidity of air moving through the rafter ducts is needed to more effectively evaluate the roof collector. This could be accomplished by wet bulb or hygrometer utilization.

Controls which would stop the system fan when relative humidity of air being forced through the hay becomes too high are needed.

Additional replications are needed to insure more conclusive results in future studies, and the studies should be performed at a time of year that would allow better performance of the solar collectors. This would include spring to fall drying when higher temperatures and solar radiation are readily available.

Hay moisture determination and air velocity measurements must be more precise in future studies. Larger moisture samples from more locations in the bales would increase accuracy of moisture determination. Air velocity measurements should be taken at regular time intervals during every cure.

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APPENDICES

APPENDIX A

AMBIENT, HEATED AND INTERNAL BALE PSYCHROMETRIC DATA

Figures 9 to 17 are included in Appendix A and represent the drying data discussed in the results. These figures represent psychrometric data from tests one and two which include ambient air, heated air and bale internal (top and center) air. The psychrometric data include vapor pressure, temperature and relative humidity. Figures 12 to 14 include bale moisture content.

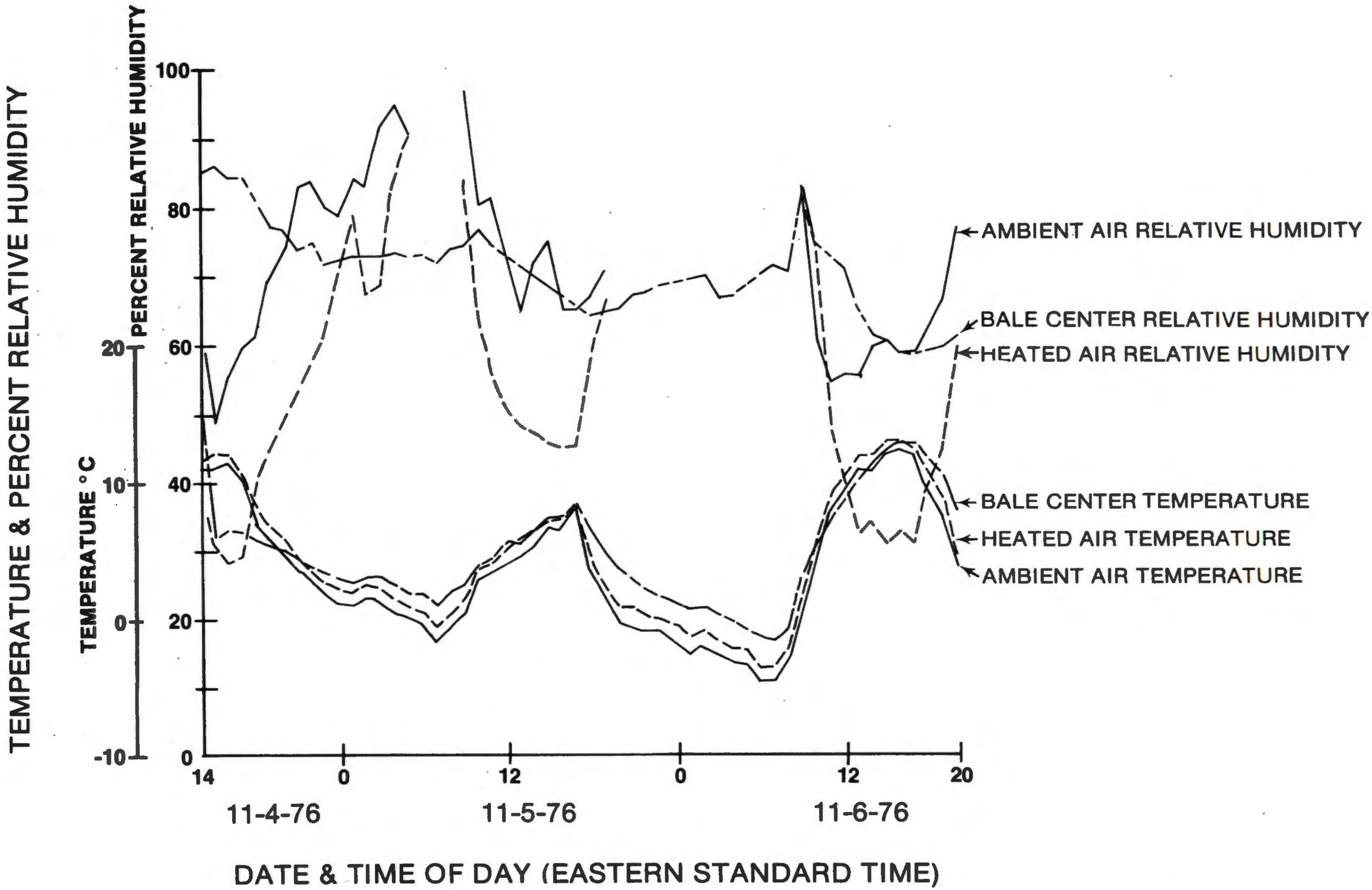

FIGURE 9. Temperature and relative humidity of ambient, heated and bale center air for Bale 5 of Test 1.

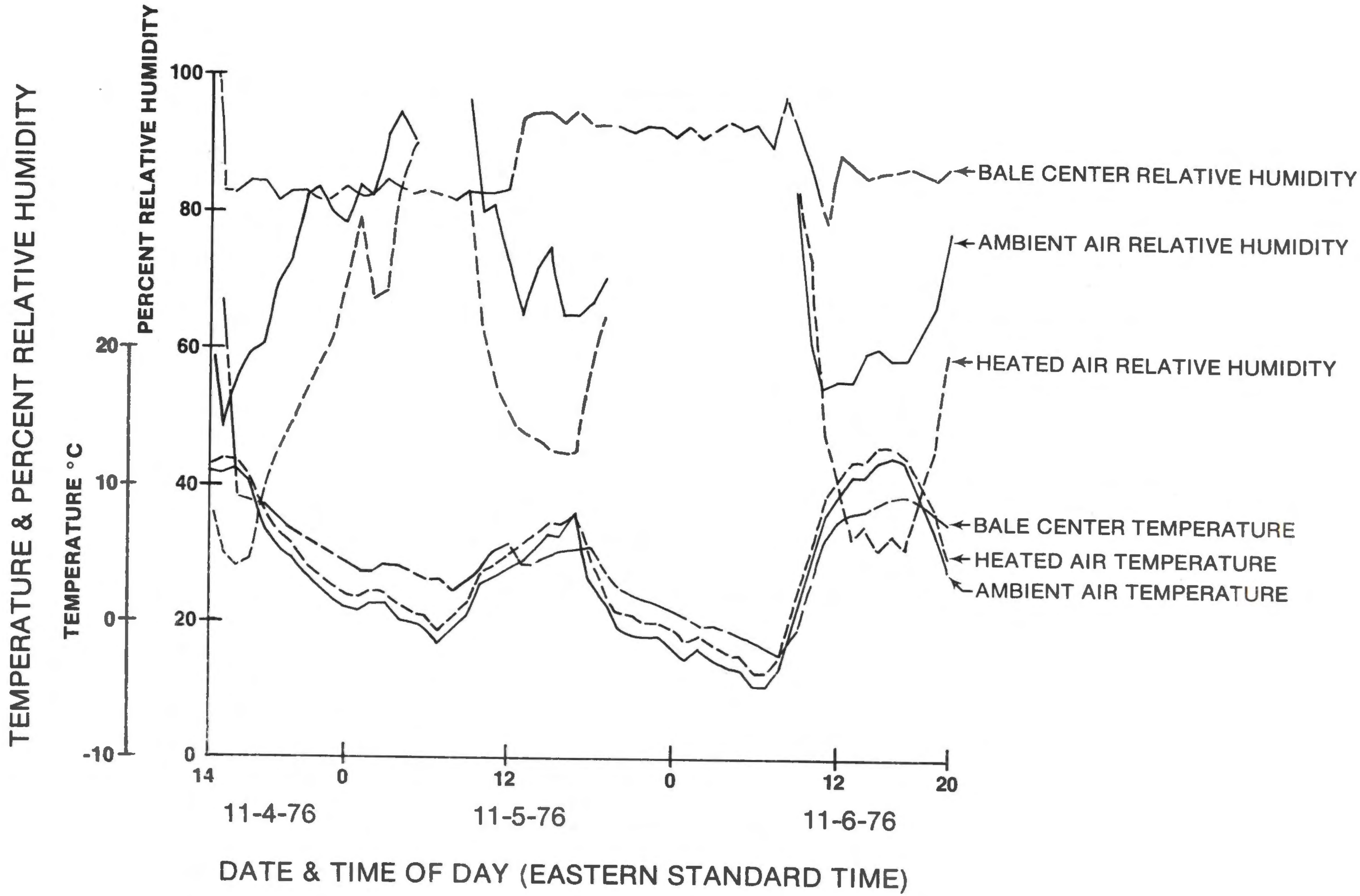

FIGURE 10. Temperature and relative humidity of ambient, heated and bale center air for Bale 4 of Test 1.

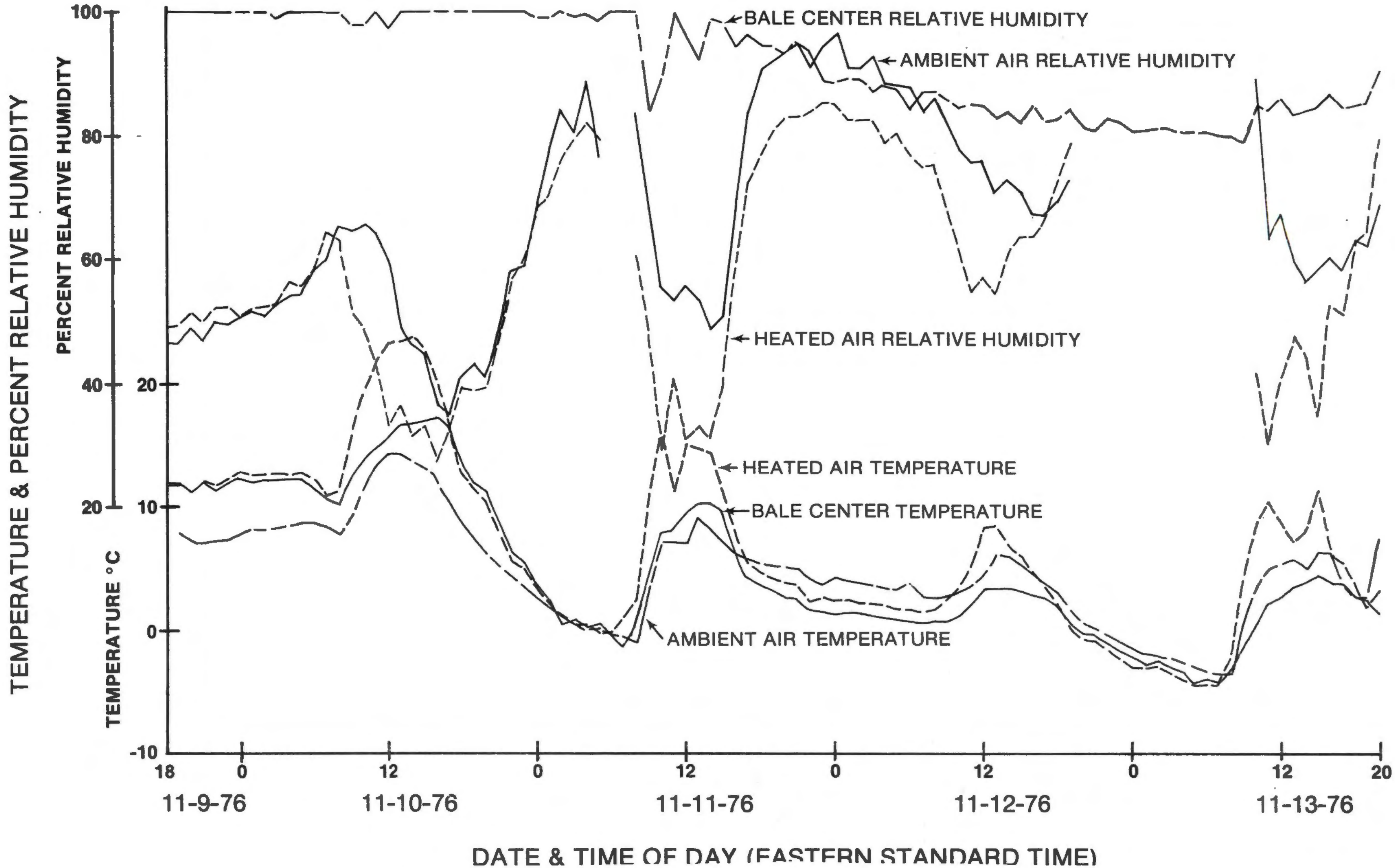

FIGURE 11. Temperature and relative humidity of ambient, heated and center bale air for Bale 4 of Test 2.

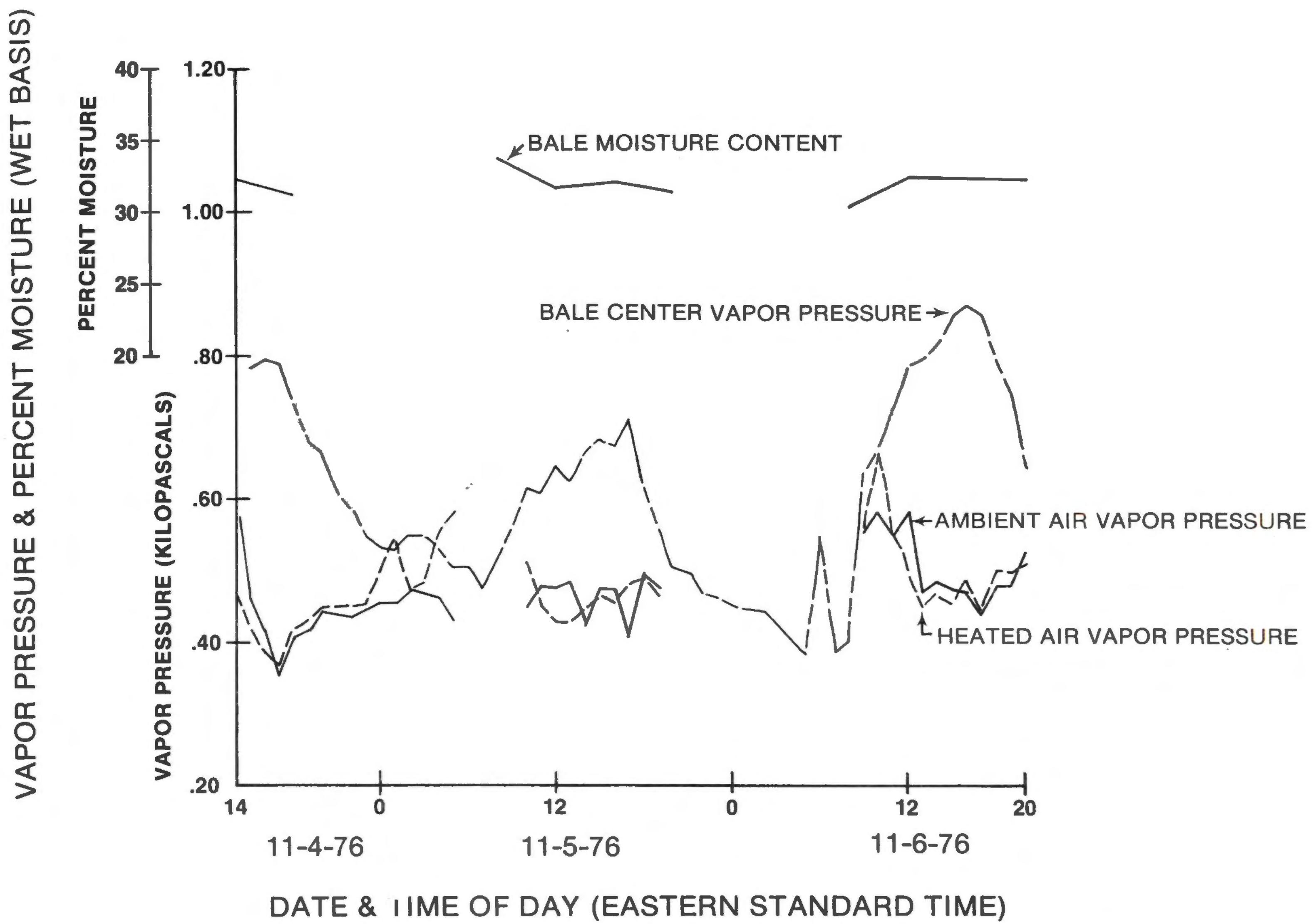

FIGURE 12. Vapor pressure of ambient, heated and bale center air and bale moisture content for Bale 5 of Test 1.

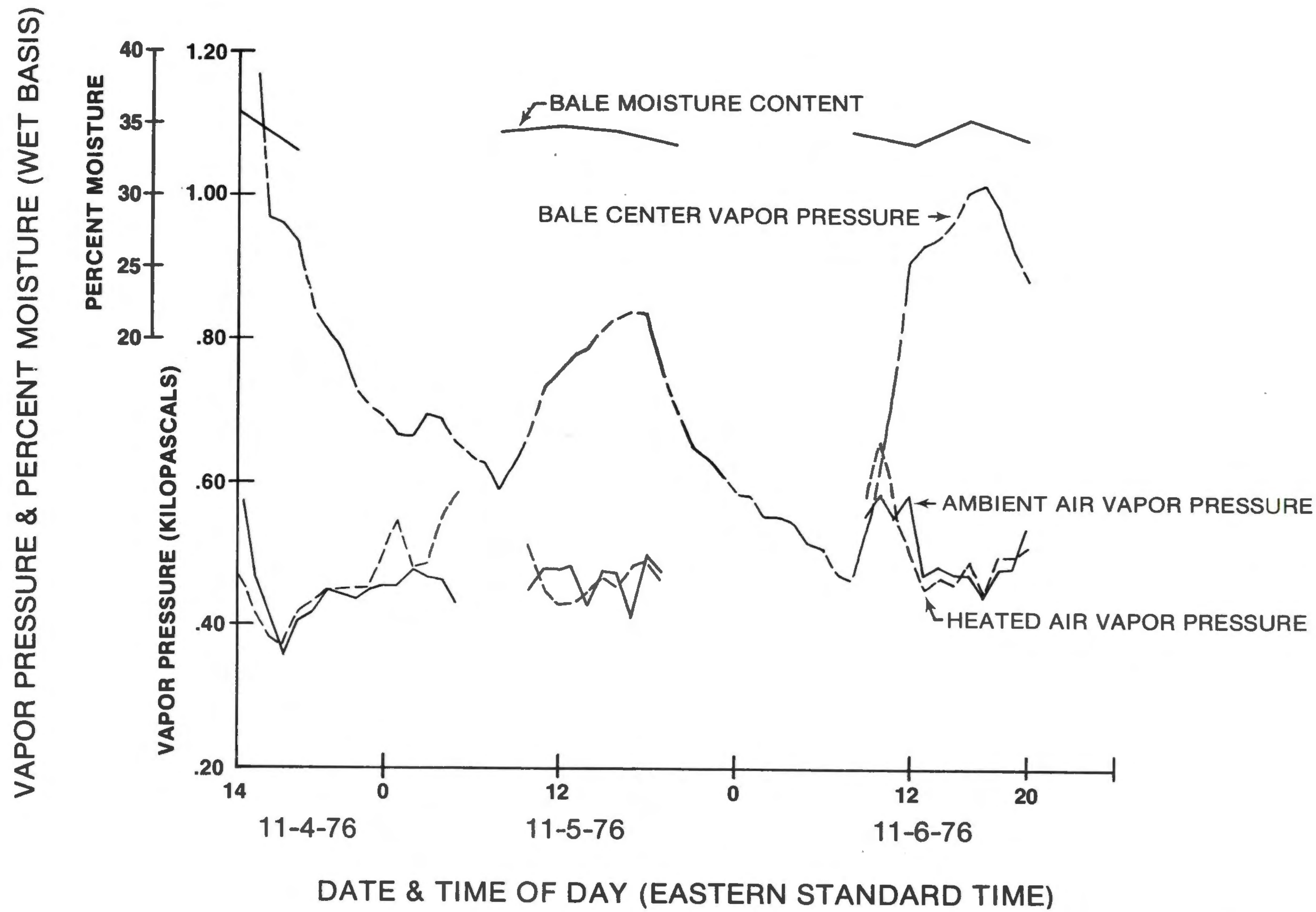

FIGURE 13. Vapor pressure of ambient, heated and bale center air and bale moisture content for Bale 4 of Test 1.

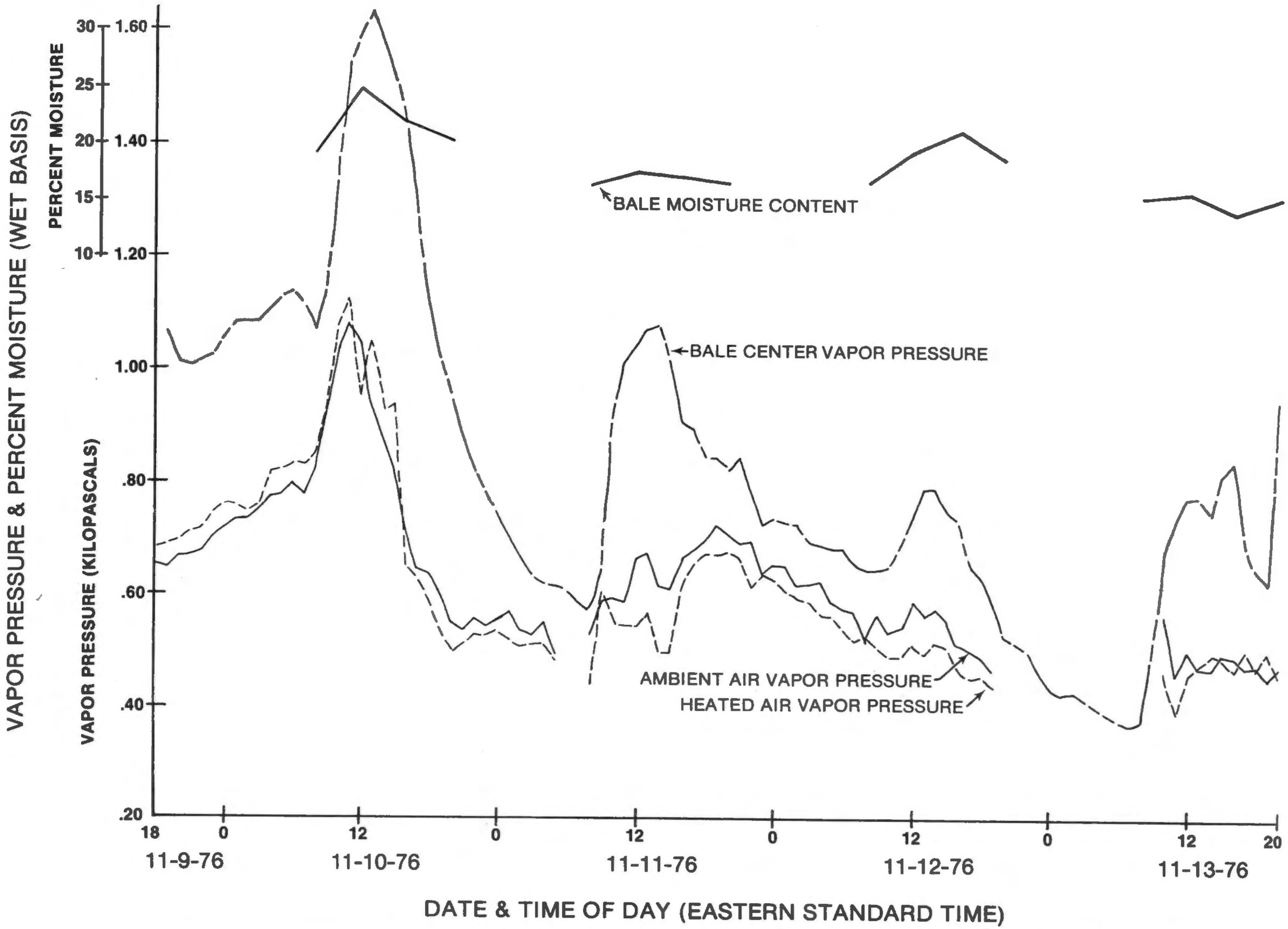

FIGURE 14. Vapor pressure of ambient, heated and bale center air and bale moisture content for Bale 4 of Test 2.

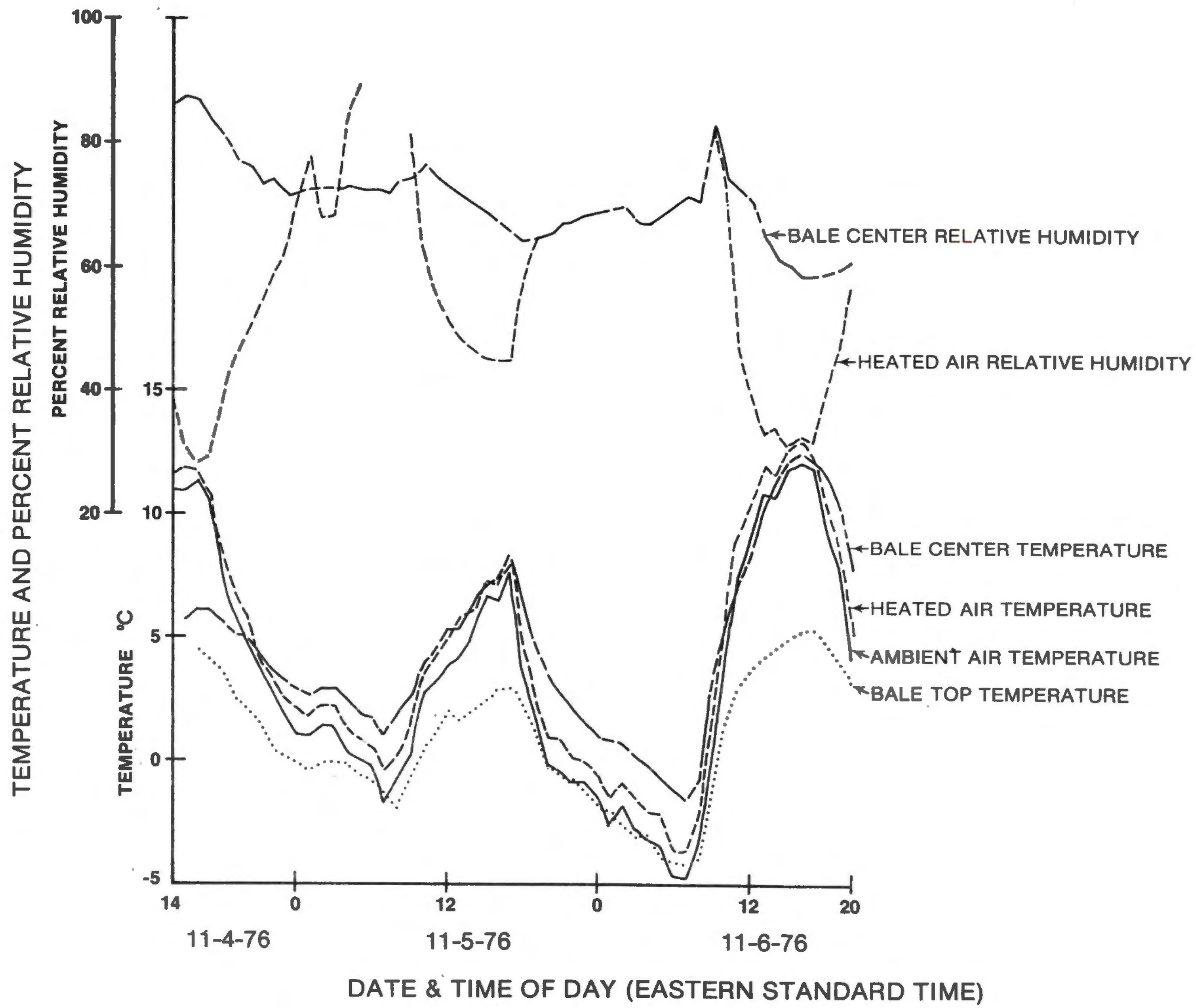

FIGURE 15. Ambient, heated and bale top and center air temperatures along with relative humidities of heated and bale center air for Bale 5 of Test 1.

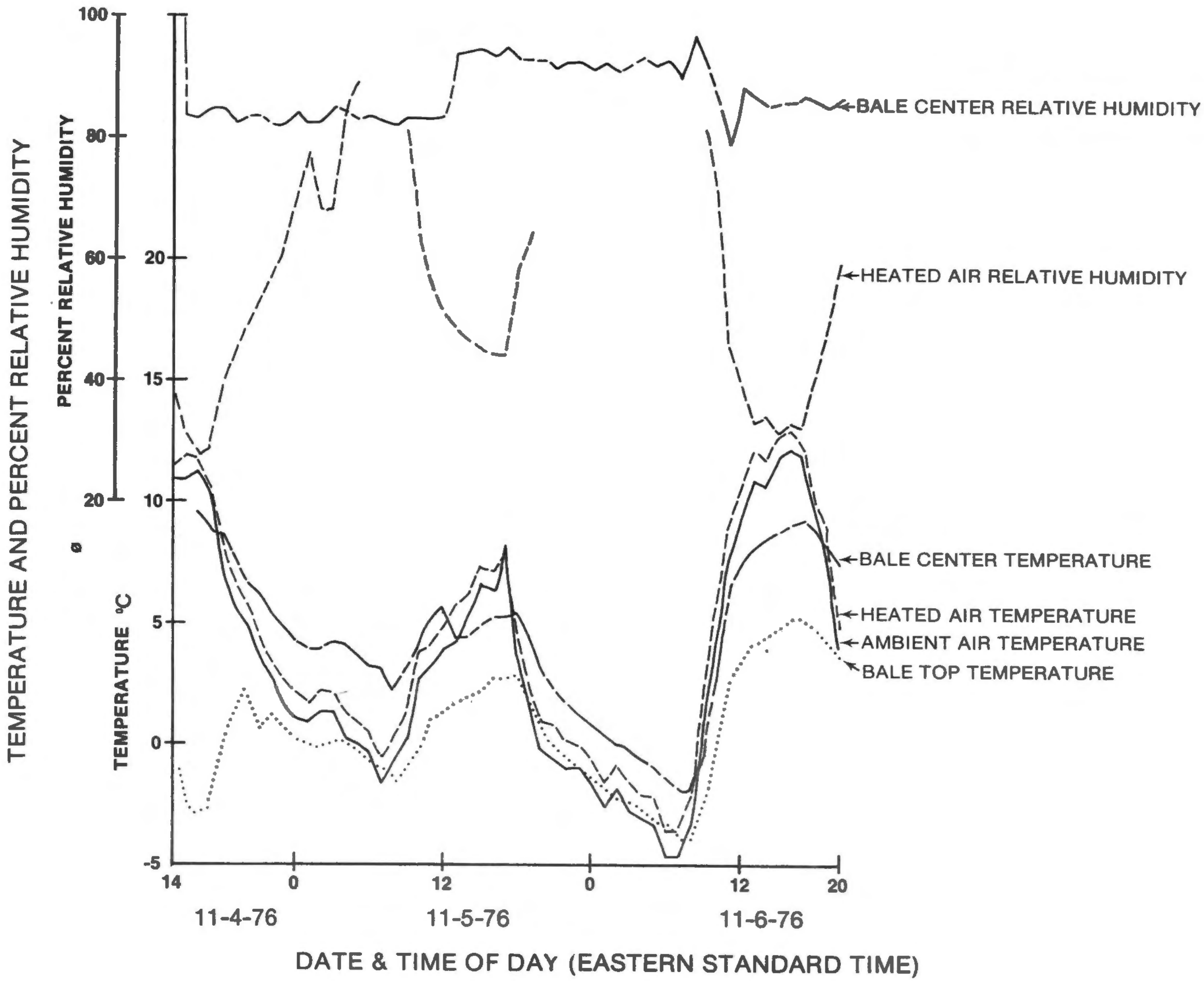

FIGURE 16. Ambient, heated and bale top and center air temperatures along with relative humidities of heated and bale center air for Bale 4 of Test 1.

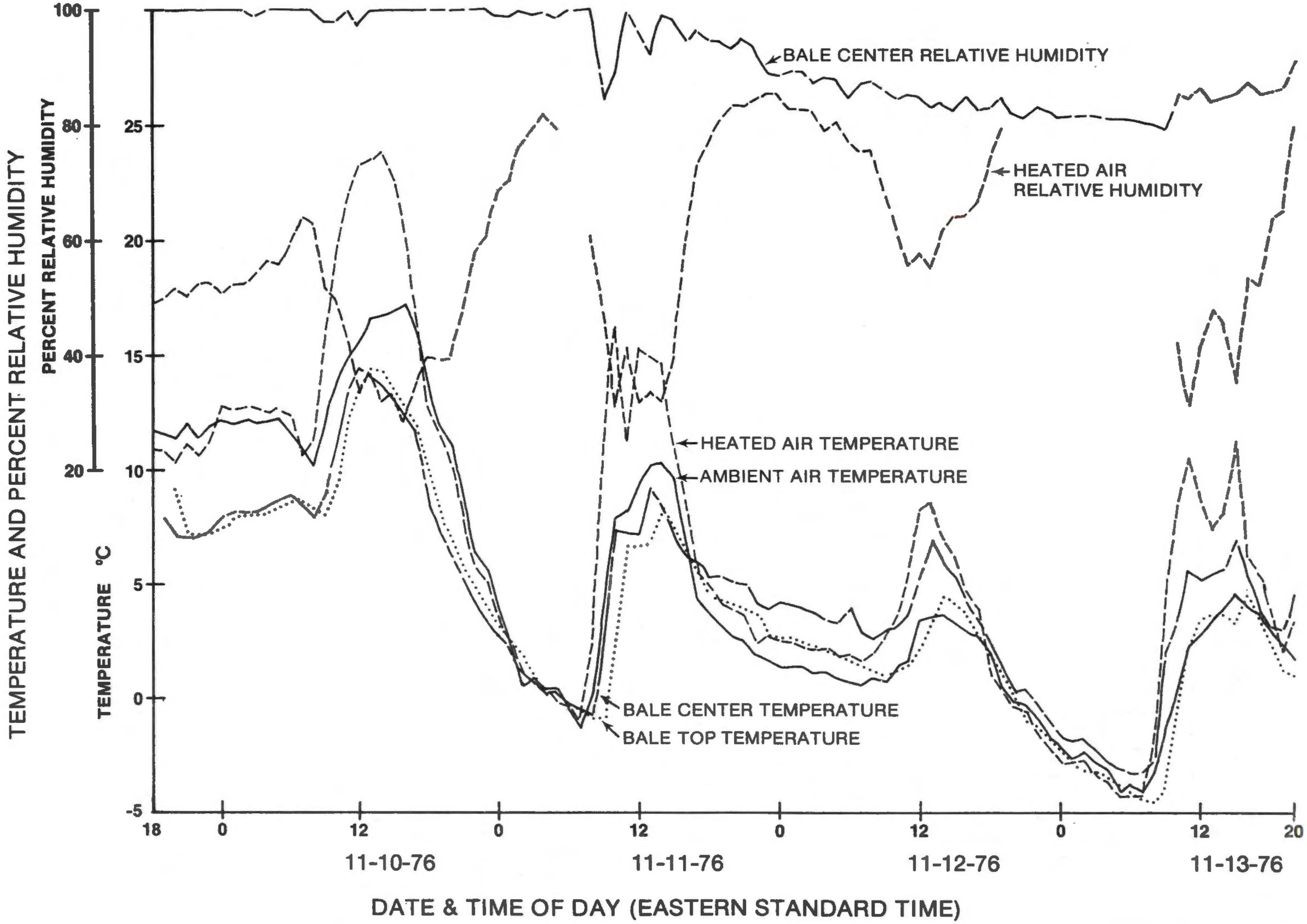

FIGURE 17. Ambient, heated and bale top and center air temperatures along with relative humidities of heated and bale center air for Bale 4 of Test 2.

APPENDIX B

MOISTURE DATA

TABLE 6. Percent wet basis moisture content as determined by core samples at given periods of time during the three tests.

Date	Time	Bales 1	2	3	4	5	Avg.
11/4/76	1400	35.7	32.7	34.5	35.9	33.1	34.1
	18	32.6	31.2	32.8	33.0	33.0	32.5
11/5/76	8	32.6	34.0	25.7	34.3	27.1	30.7
	12	31.1	31.9	31.0	34.7	28.8	31.5
	16	33.8	32.1	32.3	34.5	30.5	32.6
	20	30.9	31.4	29.7	33.6	30.4	31.2
11/6/76	8	32.6	30.6	29.5	34.4	31.4	31.7
	12	30.7	32.6	32.1	33.5	30.4	31.9
	16	32.9	32.7	33.7	35.4	29.9	32.98
	20	31.9	32.2	32.2	34.0	27.8	31.62
11/9/76	18	21.5	20.5	21.4	20.6	21.8	21.2
11/10/76	8	19.0	20.0	19.7	19.0	20.8	19.7
	12	24.0	23.3	19.5	24.5	22.3	22.7
	16	15.5	15.7	16.4	21.1	18.8	17.5
	20	18.6	17.4	18.1	20.1	18.2	18.4
11/11/76	9	18.4	15.2	15.3	16.3	15.5	16.1
	12	17.0	15.0	13.3	17.3	15.0	15.5
	16	14.4	14.1	17.8	16.9	18.5	16.3
	20	14.2	20.4	15.3	16.5	14.5	16.2
11/12/76	9	18.1	18.6	18.2	16.6	16.4	17.6
	12	17.6	15.7	15.5	19.1	16.7	16.9
	16	15.4	14.6	14.7	21.3	18.8	17.0
	20	15.0	16.5	18.0	18.3	16.8	17.0

TABLE 6. (continued)

Date	Time	Bales 1	2	3	4	5	Avg.
11/13/76	900	18.7	15.8	16.3	15.6	16.7	16.6
	12	24.2	14.4	18.0	15.9	17.1	17.9
	16	18.6	13.5	16.0	13.8	18.4	16.1
	20	14.5	17.6	13.2	15.5	14.2	15.1
11/18/76	5	25.6	37.9	43.1	32.5	39.7	35.5
11/19/76	9	25.1	36.1	41.3	37.0	34.2	35.8
	12	20.1	37.0	39.9	29.7	36.4	32.6
	16	16.5	39.0	38.7	34.5	32.1	32.2
	20	21.9	35.9	41.8	30.5	41.3	34.3
11/20/76	9	21.3	24.9	25.2	30.8	38.9	28.2
	12	20.9	34.9	39.0	27.1	40.3	32.4
	16	17.6	35.5	35.0	32.3	40.9	32.3
	18	23.0	36.9	31.6	33.1	39.3	32.8
11/21/76	8	24.1	37.7	40.7	30.8	41.3	34.9
	12	19.8	31.7	39.5	30.6	38.1	31.9
	16	22.1	36.4	41.2	21.4	35.1	31.2
	20	20.1	28.9	36.7	32.0	38.1	31.2
11/22/76	9	17.6	39.9	41.4	31.3	33.3	32.7
	12	23.5	29.1	47.9	20.5	30.8	30.4
	16	19.6	20.9	42.4	30.3	37.1	30.1
11/23/76	9	16.3	30.5	30.6	32.3	30.0	27.9
	12	13.9	32.9	11.8	36.7	31.0	25.3
	16	24.2	31.5	31.5	26.8	36.7	30.1
11/24/76	9	19.9	31.5	33.8	39.4	32.5	31.4
	12	18.8	30.2	31.0	26.9	40.1	29.4
	16	17.1	33.1	31.3	29.4	28.6	27.9

TABLE 6. (continued)

Date	Time	Bales 1	2	3	4	5	Avg.
11/30/76	1100	13.3	25.6	14.7	24.2	28.2	15.6
	16	12.0	20.8	18.3	18.3	14.6	16.8
12/1/76	9	12.4	25.2	28.1	18.1	21.2	21.0
	15	15.4	20.2	21.9	24.7	17.2	19.9
12/2/76	9	11.8	23.0	18.1	18.3	21.7	18.6
	13	13.2	20.9	20.5	23.1	21.7	19.9
	16	9.3	16.7	24.3	27.6	24.1	20.4
12/3/76	9	9.5	26.4	27.8	19.5	25.6	21.8

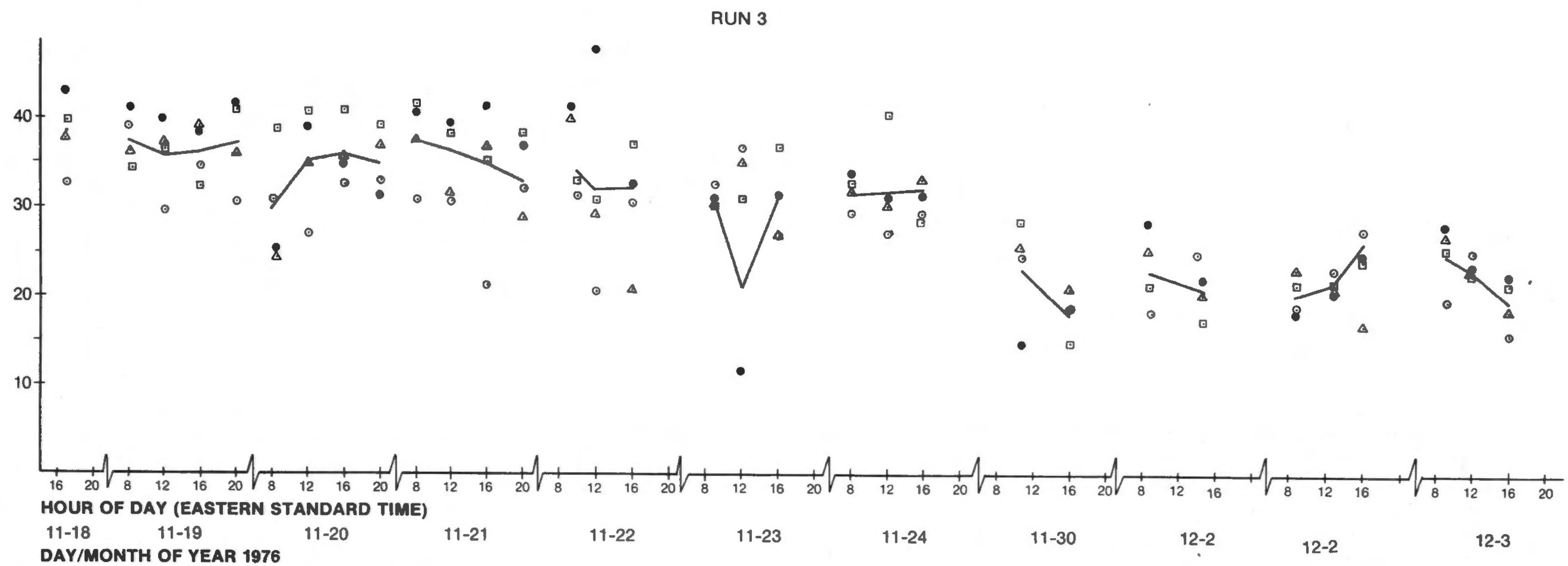

FIGURE 18. Individual bale moisture content for each of the five bales of the third test with an average for all five bales.

APPENDIX C

METHOD OF CALCULATION OF COLLECTOR EFFICIENCY

$$\text{Collected energy} = KWH/m^2\text{-day} = \frac{H - A}{H_s} \times V \times T \times \frac{60 \text{ min}}{\text{day}} \times \frac{1}{S} \times \frac{KWH - hr}{3600 \text{ kj}} .$$

where

H = Heated air enthalpy, j/kg of dry air

A = Ambient air enthalpy, j/kg of dry air,

H_s = Heated air specific volume in m^3/kg of dry air,

V = Volume of air flow in m^3/min,

T = Number of hours for accumulative solar energy, and

S = Surface area of collector in m^2.

$$\text{Efficiency} = \frac{\text{Collected energy}}{\text{Available energy}} \times 100.$$

VITA

Donald Dan Eller was born in Sparta, Tennessee, on October 30, 1949. He graduated from White County High School in June of 1967. In September of 1967, he entered Tennessee Technological University. In June of 1968 he discontinued his education and worked for four years. In September, 1972, he entered Tennessee Technological University and received a Bachelor of Science in Agricultural Science in June of 1975.

He entered Graduate School at The University of Tennessee, Knoxville, in January, 1975, and received a Master of Science degree with a major in Agricultural Mechanization in June of 1977. He is a member of Gamma Sigma Delta.

He is married to the former Nancy Joan Poteet of Sparta, Tennessee.