THE CURING PROCESS

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Introduction

Tobacco curing is a controlled drying process. Research and experience has established the rate of moisture removal required to achieve the "color" and thus the leaf chemistry desired for bright leaf type tobacco.

The temperature and humidity of the air passing through the tobacco can vary over a certain range depending on the characteristics of the tobacco. Tobacco harvested from different fields on the same farm may cure differently when exposed to the same curing environment. Certainly tobacco grown during different seasons may respond differently when exposed to the same environment. In addition to the tobacco itself, the characteristics of the barn also have an effect on the curing process. An older barn which has developed some structural cracks, or whose doors no longer seal tightly, does not subject the tobacco to the same environment that it did when it was new.

It is possible to set a temperature-humidity schedule for a general discussion of the curing process. This is done with full knowledge that each individual cure is different and that certain tobacco will cure beautifully with a schedule that is quite different from the general schedule.

Curing Schedule

A general schedule for the dry bulb and wet bulb temperature of the air entering the tobacco during a six day cure is given in Figure 1. For comparison, the corresponding relative humidity is shown as a dotted line on the figure. The thermostat settings for the dry bulb temperature schedule is given in Table 1

The dry bulb temperature in the delivery plenum was recorded on a grower's farm in Tift County, Georgia. This grower was noted for the quality of his tobacco. The recordings were made for 6 cures in 1977 and 7 cures in 1978 in four different 126 rack barns. The range for these 52 cures is shown by the shaded region in Figure 2. For comparison the "general" dry bulb temperature schedule from Figure 1 is shown as a heavy solid line.

During the 1979 season tobacco was cured in three 30 rack curing units at the Coastal Plain Experiment Station in Tifton, Georgia. These were 1/5 the size of commercial 150 rack barns and could accommodate 10 racks on each of 3 tiers. Two six-day cures and two five-day cures were completed in each unit. The dry bulb temperature range for the six-day cures is given in Figure 3a and the corresponding wet bulb temperature range is given in Figure 3b. The same data for the five day cures is given in Figures 4a and 4b respectfully.

The leaf coloring-transition phase is defined as the period when the temperature in the delivery plenum (plenum under the tobacco for a barn where the air flows upward) is below approximately 115°F. The leaf drying phase is defined as the period when the temperature in the delivery plenum is between 115° and 140°F, and the stem drying phase is the part of the cure when the temperature in the delivery plenum is greater than 140°F. The average hours per cure phase for the cures in the 30 rack barns, and on the grower's farm, are given in Tables 2, 3, and 4 respectively.

The schedule used for the cures in the 30 rack units differed from the grower's schedule primarily in the leaf drying phase. The grower used only one day to elevate the temperature from 115° to 140°F, and then used two days in the stem drying phase. This procedure is a "carry-over" from stick curing days. The only means for getting airflow through the tobacco in a stick barn for rapid leaf drying is to run the temperature up to increase natural convection. The forced airflow in a bulk curing barn gives much better control over the curing environment; consequently, it is not necessary to advance the temperature as rapidly.

Wet Bulb Temperature

The accuracy of an automatic vent control is dependent on the accuracy of the wet bulb temperature measurement. It is very difficult to measure this temperature accurately in a bulk curing barn. Wet bulb temperature was recorded at the automatic vent control sensor in the 30 rack barns at the Coastal Plain Experiment Station, and compared with measurements made with a hand held probe. The sensor was located in the center of the return plenum (above the tobacco) at the furnace room wall. The sensor wick was kept moist with a reservoir like that used in many conventional barns. The float in the reservoir was adjusted so that 10 drops per minute dripped from the wick.

The probe measurement, plotted as a dotted curve in Figures 5 and 6, is taken as the actual wet bulb temperature. The difference between the two cures is then the error in the recorded wet bulb temperature. Note in Figure 5 that there is a good agreement until the temperature is advanced for stem drying. During this phase, the humidity is so low that the wick dries faster than it is rewetted by the flow from the reservoir. In Figure 6 there is significant error in the wet bulb measurement throughout Cure 3, and good agreement during Cure 4 until the stem drying phase.

In general, wet bulb controllers do a good job during the first four days of the cure. They will over-ventilate the barn during the final two days if the wick dries out. It is good procedure to learn the characteristics of an individual barn and set the inlet vents by hand during the final two days. In all cases the wick should be changed for each cure, and the reservoir adjusted to achieve an adequate flow over the wick.

Energy Balance

The energy balance for the 12 cures in the 30 rack units s

Energy Input Energy Output

$$Q_f + Q_r \quad Q_x + Q_s + Q_m$$

89% 11% 89% + 12% - 1%

The Q_f term is the heat added (heat energy supplied by the combustion of fuel in the furnace), and the Q_r term is the heat energy released by the tobacco itself. Tobacco, like most organic matter, goes through a rippening process where oxidation takes place. Heat is generated and spoilage results if the crop is not properly ventilated. Heat given off by the tobacco as a result of respiration, and as a by product of the complex chemical reactions that take place during curing, equals 11% of the total heat energy required.*

The Q_x term is the energy in the exchanged air, defined as the energy in the exhaust air minus the energy in the inlet air. The exhaust air contains moisture it has picked up from the tobacco. It takes 1000 to 1200 Btu's to evaporate each pound of water. This energy is known as latent heat. Sensible heat added to the inlet air as it passes through the furnace becomes latent heat in the exhaust air. During a tobacco cure the exhaust air always has a higher humidity than the inlet air; consequently, it always has a higher latent heat content. It also has a higher dry bulb temperature for most of the cure; consequently, it has a higher sensible heat content. The section of the proceedings on psychrometrics gives more detail on energy in air at a given temperature and humidity.

The Q_s term is the energy required to elevate and maintain the temperature of the barn, and is discussed in detail in the section of the proceedings on structural heat loss. This is the energy that would be required if a barn was tightly sealed and operated empty using the same thermostat settings used for an actual cure.

For insulated barns setting on foundation pads insulated from the ground, the Q_s energy is typically 10 to 20% of the total. As shown in the energy balance, it averaged 12% for the 12 cures in the 30 rack units.

The Q_m term is the sensible heat stored in the tobacco. At the beginning of the cure the green tobacco is at 95^{o}F. At the end of the cure the dry leaf is at 165^{o}F. Obviously, the leaf is hotter at 165^{o}F than at 95^{o}F, but it weighs considerably less. Only 10 to 20% of the initial mass remains at the end of a tobacco cure. For this reason the total heat energy stored in the tobacco (sensible heat) is less at the end of the cure than at the beginning.

* See discussion under "Solids Los During Curing.

It is helpful to lump the Q_x and Q_m terms together as the total energy consumed by the tobacco. On this basis then, 88% of the heat energy required for curing in an insulated barn goes into the tobacco, and 12% goes into the barn, or is lost. It is interesting to note that the energy released by the tobacco (Q_r) is approximately equal to the energy required to elevate and maintain the temperature of the barn (Q_s). In a well managed cure in an insulated barn, the heat added (Q_f) is approximately equal to the heat energy in the exchanged airstream (Q_x).

Water Removal Rate

In general, 80 to 90% of the total weight of green leaf loaded into a tobacco barn is water. The moisture content of the green tobacco cured in these 12 cures was measured and found to range from 80.4 to 84.1%. This measurement was used to calculate the total water removed during the cure. The percentage of this water that was removed each day of the cure is given in Table 2 for the 6-day cures and Table 3 for the 5-day cures. On the average, 48% was removed during the leaf coloring-transition phase (Days 1-3), 42% during the leaf drying phase (Days 4-5), and 10% during the stem drying phase (Day 6) for the 6-day cures. For the 5-day cures, 47% was removed during the leaf coloring-transition phase (Days 1-3), 30% during the leaf drying phase (Day 4), and 23% during the stem drying phase (Day 5).

For comparison the corresponding water removal percentages in a 126 rack barn on the grower's farm are given in Table 4. These percentages were calculated for 6 cures during the 1977 season and 8 cures during the 1978 season.

Airflow Required for Bulk Curing

Early research on bulk curing established that an airflow velocity of 30 feet per minute (ft./min.) across the surface of the leaf will dry it in an acceptable manner. This velocity is a design minimum for field conditions. Slightly higher air velocity will give better control of the curing conditions and make the system "more forgiving." Small mistakes in temperature advance and exchanged air control will not affect the cure as much if the airflow is 10 to 50% greater than the design minimum.

Typically, the static pressure in the delivery plenum of a three tier bulk rack barn will be 0.8 to 1.0 inches of water column (in. WC) at the beginning of the cure and 0.1 to 0.3 inches at the end. As the tobacco dries, the resistance decreases and the airflow increases. Airflow through the tobacco can be determined by measuring the static pressure and then reading the corresponding flow from the fan performance curve. A curve developed from data taken with the fan in place in the barn must be used. The barn structure and placement of the fan in the barn affect the performance, consequently, a performance curve based on data taken on a laboratory test stand is not appropriate. Airflow parameters for three cures in the 30 rack barns are given in Tables 5-7 to illustrate the range found in three tier bulk rack units.

Cure 2 in Barn 1 (Table 5) had the minimum airflow of all six 6-day cures. The velocity increased from 36 to 57 ft./min. while the static pressure decreased from 0.96 to 0.24 in. WC. In comparison Cure 1 in Barn 2 (Table 7) had the maximum airflow for all six 6-day cures. For this cure the velocity increased from 46 to 59 ft./min. while the static pressure dropped from 0.81 to 0.15.

It is difficult for a grower to determine the airflow in his barn. Fortunately, the commercial equipment available appears to provide adequate airflow for successful curing. The manufacturer's loading recommendations should be followed. If a barn is not uniformily loaded, then airflow problems can result. Specifically, the air will channel through the loosely packed areas and by-pass the tightly packed areas. As a frame of reference for loading bulk racks, the range for the cures in the 30 rack barns was 107 to 123 lbs. green leaf per rack. Some growers load the first priming tobacco at this rate and increase the loading for the upper stalk tobacco.

Exchanged Air Rate

Data was taken on the 12 cures at the Coastal Plain Experiment Station to define the exchanged air rate. These rates are presented as air changes per hour. One air change per hour means that the air in the curing compartment is replaced each hour. Sixty air changes per hour means that the air in the curing compartment is replaced each minute. The curing compartment is the space within the barn that is filled with tobacco. The volume of the curing compartment is defined to be the area of the drying floor times the height of the loading doors. The range of exchanged air rates, and the average for each of the six 6-day cures is given in Table 8. Similiar data for the 5-day cures is given in Table 9.

The exchanged air percentages given in Tables 5-7 can be compared to the exchanged air schedule presented as air changes per hour in Table 8. A relatively small percentage of the total circulated air is exhaust during the cure. Tobacco curing is a controlled drying process over a 5 to 6 day period. If the tobacco is dried too slowly it goes through the yellow or golden leaf color and begins to brown. The solids loss is also increased. If it is dried too quickly, the lamina at the butt of the leaf and around the main veins doesn't have time to finish coloring.

The average loading density for the 12 cures in the three 30 rack barns ranged 107 to 123 lbs. green leaf per rack. The loading density, based on the curing compartment volume, was then 7 to 8 lbs. green leaf per cubic foot. If a greater loading density is used, then the air changes per hour must be increased proportionally to maintain the desired moisture removal rate. For example, if tobacco is packed into boxes at a 12 lbs. per cubic foot loading density, then the exchanged air rate must be at least 50% greater than the rates shown in Tables 8 and 9. Research has shown that a 15 lbs. per cubic foot loading density requires an exchanged air rate up to 230 air changes per hour. Here the exchanged air rate was based on the volume of the boxes, not the volume of the curing compartment.

Solids Loss During Curing

The energy released by the tobacco during curing (Q_r term in the energy balance) ~~is not free. It~~ results primarily from the oxidation or breakdown of the leaf sugar. When sugar breaks down, carbon dioxide gas and water vapor are produced and heat is released. The carbon dioxide and water vapor are removed by the drying air passing through the tobacco. Anyone who has opened a bulk barn during the cure can appreciate that gasses are given off during the curing process. In effect, part of the leaf is "burned up" during curing.

The percentage of solids present at the beginning of the cure which were not present at the end is presented in Table 10 for the 12 cures in the 30 rack units. Note that the percentages range from 5.3 to 29.6%. If these two extremes are eliminated, then the average solids loss is 19.9%. This means that approximately 20% of the harvested leaf was consumed in these cures. A 10% loss has been measured in one set of laboratory experiments. It is safe to say that the solids loss during a "typical" tobacco cure is between 10 and 20%. There is a need for further research to evaluate different cure management strategies in terms of energy consumption and solids loss.

Energy Consumption versus Stalk Position

It takes more energy to cure lower stalk tobacco than upper stalk tobacco. This is because the first priming tobacco has a higher moisture content. Let's assume that the first priming has a moisture content of 90%. This means that 0.9 pounds of water must be removed to obtain 0.1 pounds of dry leaf solids. If we assume that there is a 15% solids loss during the cure, and that the leaf is reordered and sold at 20% moisture content, then 0.9 pounds of water is removed for each 0.106 pounds of marketed leaf. The average heat of vaporization (heat to evaporate the water) during a tobacco cure is 1113 Btu/lb. This translates to 0.0139 gallons of LP gas (87.5 % combustion efficiency) for each pound of water removed. The fuel consumption based solely on water removal is then

$$\frac{0.9\ (0.0139)}{0.106} = 0.12\ \text{GLP/lb. marketed leaf}$$

(GLP - gallons of LP gas)

The top leaves or tips typically have a moisture content of 80%. In this case 0.8 pounds of water are removed to obtain 0.2 pounds of dry leaf solids, or 0.212 pounds of marketable leaf. The fuel consumption based solely on water removal is

$$\frac{0.8\ (0.0139)}{0.212} = 0.05\ \text{GLP/lb. marketed leaf}$$

It takes more than twice as much energy to remove the moisture from the first priming tobacco as it does the last priming tobacco.

Comparison of 30 Rack and 126 Rack Barns

The manufacturer who built the barns on the Talley Farm, built the 30 rack barns as scaled down models of their 126 rack barn. The 30 rack barns and the 126 rack barn both had the same insulation in the side walls, doors, and ceiling of the curing compartment. Both had the same insulation in the furnace room and both were insulated from the ground with the same insulation. (See section on structural heat loss in this Proceedings for a description of the technique used to insulate the foundation pad from the ground.) It is valid then to compare the energy efficiency of the cures in the 30 rack barns with the cures on the grower's farm in his 126 rack barn. This is done in Table 11 on the basis of gallons of LP gas equivalent per lb. of marketed leaf (GLP/lb. leaf). The total tobacco marketed from the grower's barn in 1977, 1978, and 1979 was divided into the total fuel consumed for those years to obtain the GLP/lb. marketed leaf ratios. The same procedure was used to obtain this ratio for the 12 cures (six 6-day and six 5-day cures) in the 30 rack barns.

A comparison of Tables 4 and 12 shows that the grower used, on the average, 20% of the fuel consumption to remove 19 percent of the moisture during the leaf coloring-transition phase of the 1977 cures. He used 44% of the fuel to remove 33% of the moisture during stem drying. The percentages for the 1978 cures are similiar. This illustrates an obvious point, one that is appreciated by all involved in tobacco curing. Moisture removal is by far the dominant factor in energy consumption. The amount of water removed from the 1977 cures on the Talley farm averaged 1000 gallons per cure, and during 1978 the average was 940 gallons per cure. The fuel required to evaporate this water, without considering the heat required to elevate and maintain the temperature of the barn, would be 116 GLP per cure for the 1977 cures and 107 GLP per cure for the 1978 cures. For comparison the measured LP gas consumption averaged 149 gallons per cure in 1977 and 158 gallons per cure in 1978.

Electrical Energy Consumption

In general, the electrical energy required for tobacco curing in an insulated bulk curing barn is 10 to 20% of the total energy consumption. The measured electrical energy for the 12 cures in the 30 rack units was 17% of the total. On the grower's farm, the measured electrical energy consumption averaged 499 Kw-hr. per cure for the 1977 season (6 cures) and this was 12% of the total energy consumption. For the 1978 season (8 cures) the consumption was 656 Kw-hr. per cure or 15% of the total.

In order to convert Kw-hr. and gallons of LP gas to a common base for comparison, use the following procedure

No. Kw-hr. x 3413 = ___ Btu of Electrical Energy
No. Gallons LP x 91,600 = ___ Btu of LP Gas Energy
No. Gallons Fuel Oil x 140,000 = ___ Btu of Fuel Oi Energy

The percentage of the total energy consumed which is electrical, is then

$$\% = \frac{\text{Btu Electrical Energy x 100}}{\text{Btu Petroleum Fuel Energy}}$$

Comparison of 6 Day and 5 Day Cures

When fully ripened tobacco is harvested, it is often possible to shorten the leaf coloring phase and finish the cure in 5 days. The heat energy required for the six 5-day cures in the 30 rack units was 7% less then the heat energy required for the six 6-day cures. It does not take a great deal of heat energy to maintain the leaf coloring environment, consequently, the savings realized by shortening this phase is not proportional to the number of hours the curing time is reduced.

It is good management to use only the number of hours in the leaf coloring phase required to achieve the color uniformity associated with good quality. Electrical energy consumption is proportional to fan operating hours, consequently, when 24 hours is subtracted from a 144 hour cure the reduction is 17%. The actual measured reduction for the cures in the 30 rack units was 19.6%. The total (Electrical + heat) energy reduction for the 5-day cures in comparison with the 6-day cures was approximately 9%.

1. Thermostat settings for a "typical" 6 day cure.

	Cure Phase	Thermostat Setting, ^{o}F	Adjustment
0		95	
	Leaf Coloring		
24		95	
	Leaf Coloring		
		95	Automatic Advance at $1^{o}F/hr$ to 115
	Transition		
72		115	Automatic Advance at $1^{o}F/hr$ to 130
	Leaf Drying		
96		130	Automatic Advance at $1^{o}F/hr$ to 140
	Leaf Drying		
120		140	Automatic Advance at $3^{o}F/hr$ to 165
	Stem Drying		
144		165	

Table 2. Daily water removal percentages for six 6-day cures in 30 rack barns at the Coastal Plain Experiment Station, Tifton, Georgia.

Day	Range, %	Average, %	Cure Phase
1	6-12	8	48% Leaf Coloring-Transition
2	12-20	16	(Average 77 Hours)
3	15-23	18	
4	26-33	29	42% Leaf Drying
5	18-26	21	(Average 41 Hours)
6	5-12	8	10% Stem Drying (Average 26 Hours)

Table 3. Daily water removal percentage for six 5-day cures in 30 rack barns at the Coastal Plain Experiment Station, Tifton, Georgia.

Day	Range, %	Average, %	Cure Phase
1	7-17	13	47% Leaf Coloring-Transition
2	15-17	16	(Average 65 Hours)
3	23-26	25	30% Leaf Drying (Average 24 Hours)
4	28-34	32	23% Stem Drying
5	9-19	14	(Average 31 Hours)

Table 4. Water removal percentages for cures in 126 rack barn on the Talley Farm, Tift County, Georgia.

1977 Season (6 Cures)

Range, %	Average, %	Cure Phase
15-29	19	Leaf Coloring-Transition (Average 72 Hours)
38-60	48	Leaf Drying (Average 25 Hours)
22-39	33	Stem Drying (Average 40 Hours)

1978 Season (8 Cures)

13-25	18	Leaf Coloring-Transition (Average 64 Hours)
31-43	40	Leaf Drying (Average 24 Hours)
32-52	42	Stem Drying (Average 61 Hours)

Table 5. Static pressure in the delivery plenum, velocity of air through the tobacco and percentage of total circulated air exhausted during Cure 2 in Barn 1 (30 rack) at the Coastal Plain Experiment Station, Tifton, Georgia.

Hour	Static Pressure in. WC	Airflow ft./min.	Exchanged Air Percentage
0	0.96	36	
			4
24	0.84	44	
			10
48	0.67	50	
			8
72	0.59	51	
			13
96	0.48	51	
			8
120	0.31	53	
			4
144	0.24	57	

Table 6. Static pressure in the delivery plenum, velocity of air through the tobacco and percentage of total circulated air exhausted during Cure 2 in Barn 3 (30 rack) at the Coastal Plain Experiment Station, Tifton, Georgia.

Hour	Static Pressure in. WC	Airflow ft./min.	Exchanged Air Percentage
0	0.92	39	
			4
24	0.81	46	
			10
48	0.74	49	
			10
72	0.64	50	
			11
96	0.39	52	
			6
120	0.31	53	
			3
144	0.21	56	

Table 7. Static pressure in the delivery plenum, velocity of air through the tobacco and percentage of total circulated air exhausted during Cure 1 in Barn 2 (30 rack) at the Coastal Plain Experiment Station, Tifton, Georgia.

Hour	Static Pressure in. WC	Airflow ft./min.	Exchanged Air Percentage
0	0.81	46	
			10
24	0.61	50	
			8
48	0.52	51	
			15
72	0.48	51	
			16
96	0.35	52	
			9
120	0.18	57	
			5
144	0.15	59	

Table 8. Exchanged air rates for six 6-day cures in 30 rack barns at the Coastal Plain Experiment Station, Tifton, Georgia.

Day	Air Changes per Hour* Range	Average
1	14-39	23
2	33-66	41
3	34-65	49
4	46-70	62
5	26-41	36
6	14-25	21

Based on curing compartment volume

Table 9. Exchanged air rates for six 5-day cures in 30 rack barns at the Coastal Plain Experiment Station, Tifton, Georgia.

Day	Air Changes per Hour* Range	Average
1	13-37	30
2	25-37	32
3	34-63	48
4	25-55	39
5	20-34	25

* Based on curing compartment volume

Table 10. Measured percentage solids loss during the 12 cures in the 30 rack barns at the Coastal Plain Experiment Station, Tifton, Georgia.

Cure No.	Barn 1	Barn 2	Barn 3
1	18.2	17.7	5.3
2	17.0	21.1	29.6
3	23.2	20.4	20.4
4	18.8	20.4	21.4
Average	19.6	19.9	19.2

Table 11. Comparison of energy efficiency in 30 rack barns with a 126 rack barn on the Talley Farm, Tift County, Georgia.

Barn	Seasonal Average (GLP/lb. Market Weight)
126 Rack	
1977 (7 Cures)	.079
1978 (8 Cures)	.089
1979 (6 Cures)	.075
30 Rack	
1979 (12 Cures)	.080

Table 12. Fuel consumption percentages for cures in 126 rack barn on the Talley Farm, Tift County, Georgia.

1977 Season (6 Cures)

Cure Phase	Range, %	Average, %
Leaf Coloring-Transition	16-28	20
Leaf Drying	34-56	44
Stem Drying	26-39	36

1978 Season (8 Cures)

Cure Phase	Range, %	Average, %
eaf Coloring-Transition	13-24	17
Leaf Drying	28-45	36
Stem Drying	36-57	47

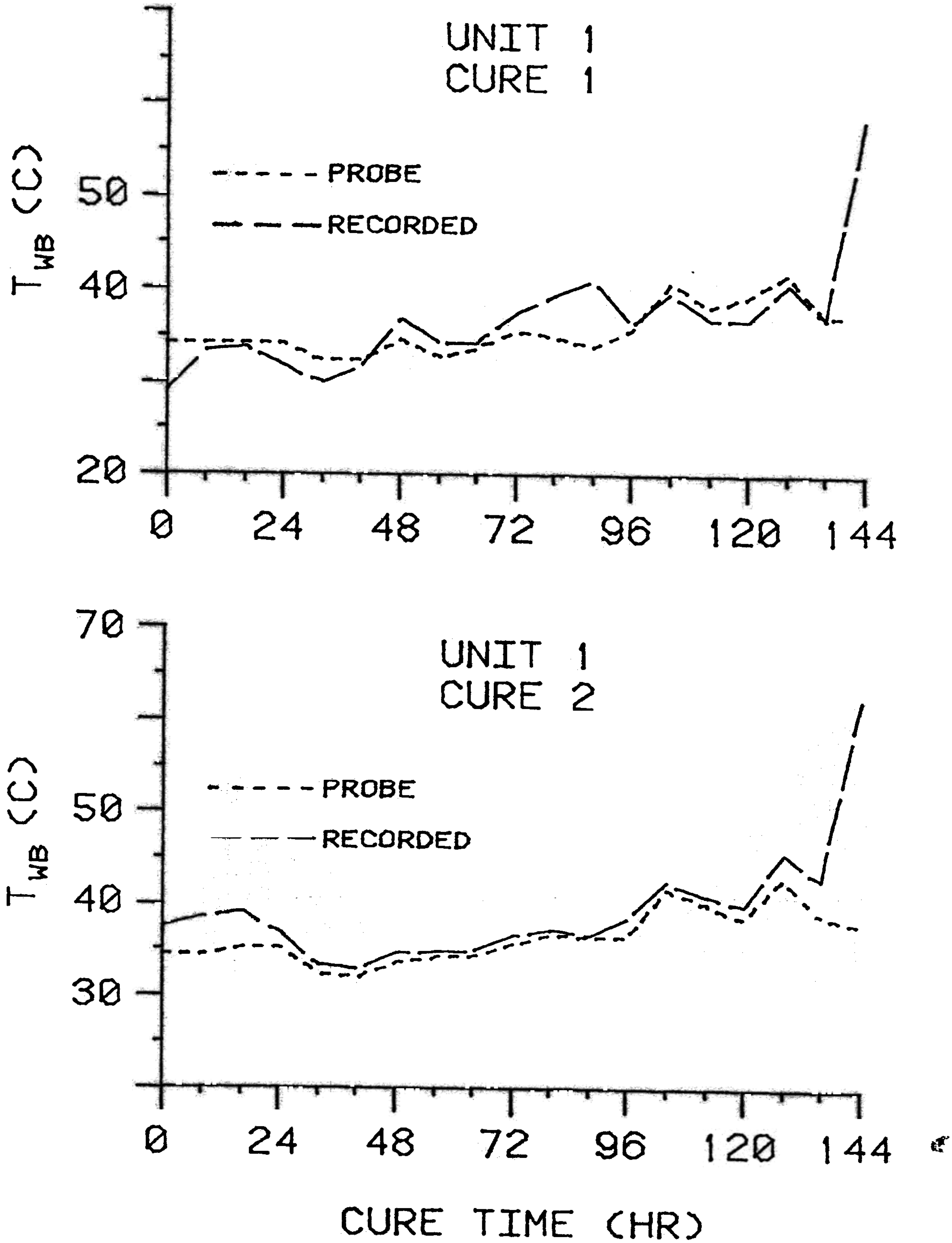

Figure 5. Comparison of wet bulb temperature recorded at the vent control sensor and the actual wet bulb temperature (dotted curve) during Cures 1 and 2 in Barn 1 at the Coastal Plain Experiment Station, Tifton, Georgia.

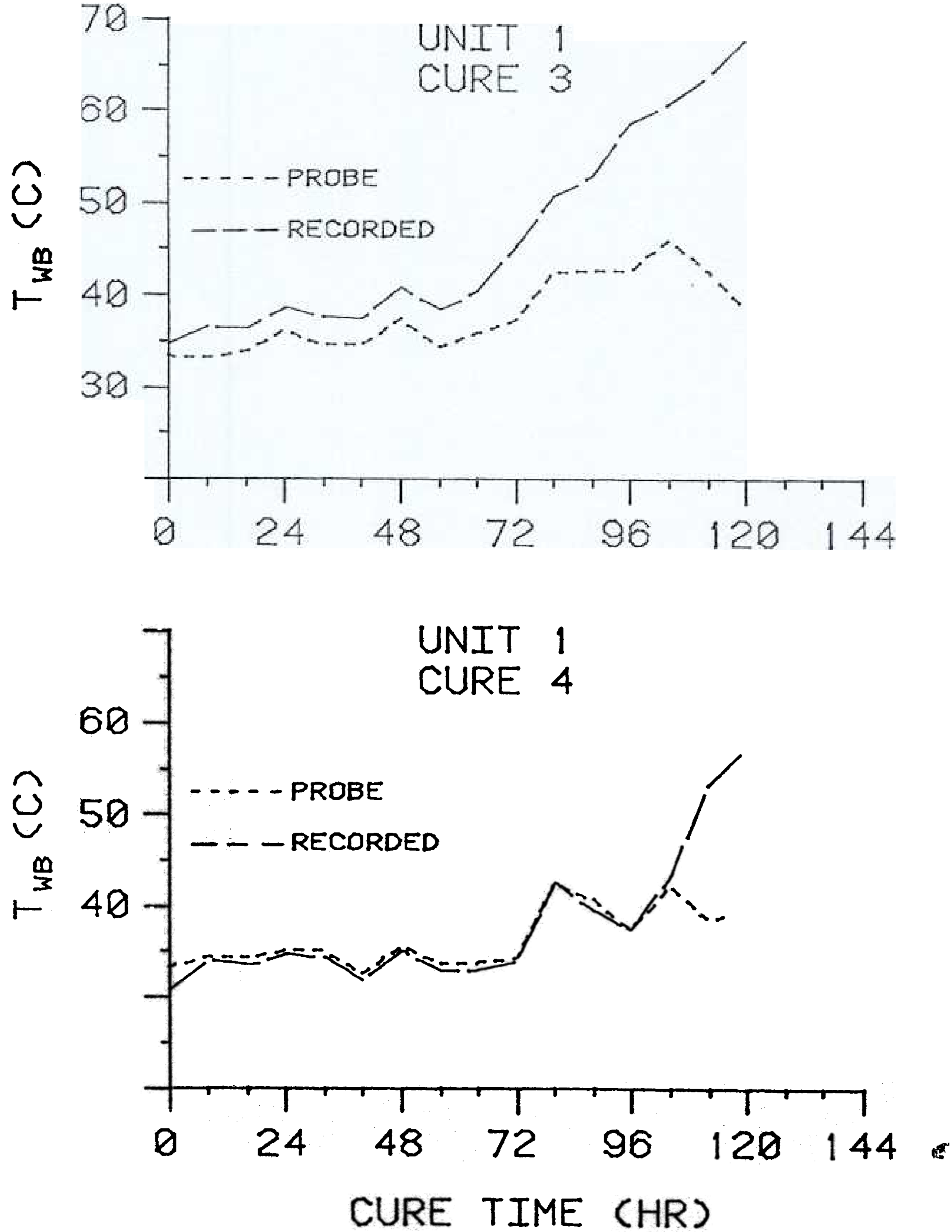

Figure 6. Comparison of wet bulb temperature recorded at the vent control sensor and the actual wet bulb temperature (dotted curve) during Cures 3 and 4 in Barn 1 at the Coastal Plain Experiment Station, Tifton, Georgia.

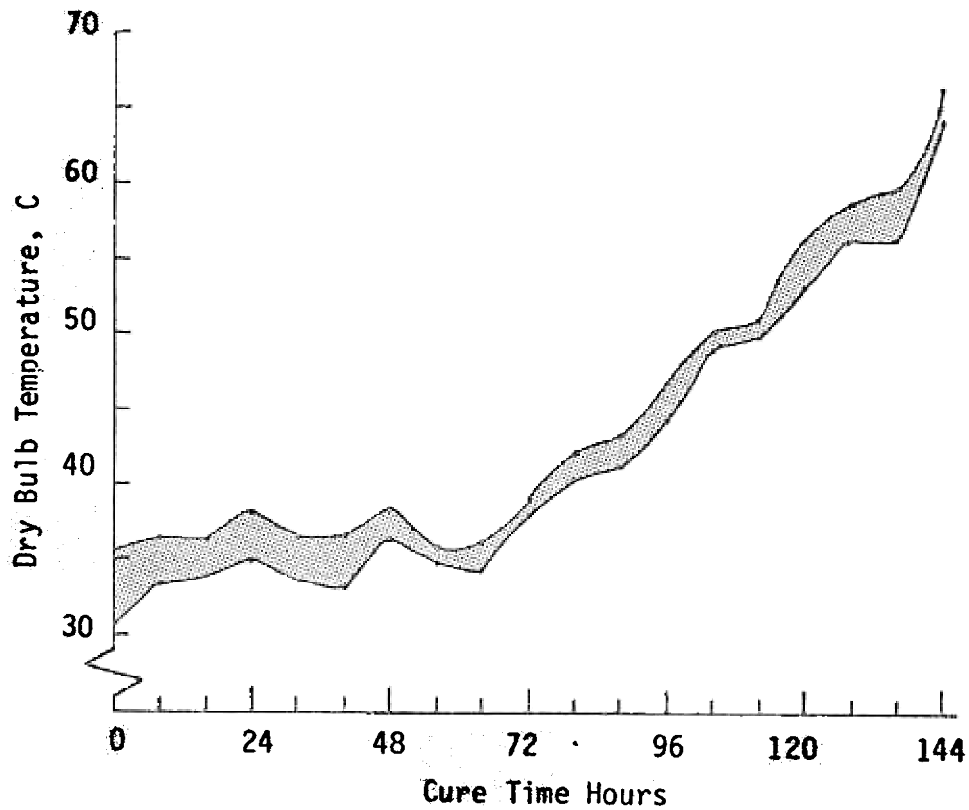

Figure 3a. Dry bulb temperature range for six 6-day cures in the 30 rack barns at the Coastal Plain Experiment Station, Tifton, Georgia.

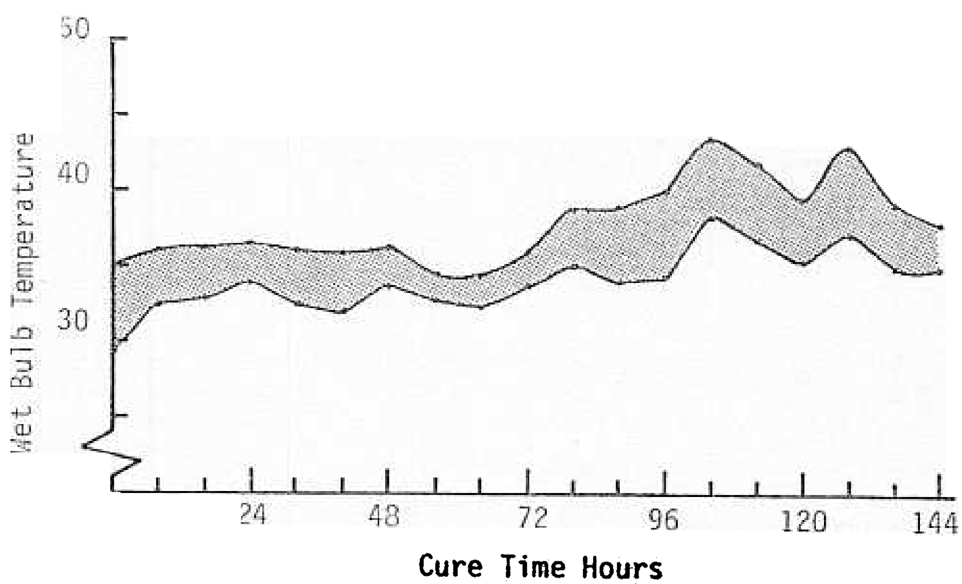

Figure 3b. Wet bulb temperature range for six 6-day cures in the 30 rack barns at the Coastal Plain Experiment Station, Tifton, Georgia.