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Heat-Pump-Dehumidification During the Curing of Flue-Cured Tobacco

Bryan W. Maw
J. Michael Moore
Michael G. Stephenson
Paul E. Sumner

Conversion Table

U.S. Abbr.	Unit	Approximate Metric Equivalent
	Length	
mi	mile	1.609 kilometers
yd	yard	0.9144 meters
ft *or* '	foot	30.48 centimeters
in *or* "	inch	2.54 centimeters
	Area	
sq mi *or* mi^2	square mile	2.59 square kilometers
acre	acre	0.405 hectares *or* 4047 square meters
sq ft *or* ft^2	square foot	0.093 square meters
	Volume/Capacity	
gal	gallon	3.785 liters
qt	quart	0.946 liters
pt	pint	0.473 liters
fl oz	fluid ounce	29.573 milliliters or 28.416 cubic centimeters
bu	bushel	35.238 liters
cu ft *or* ft^3	cubic foot	0.028 cubic meters
	Mass/Weight	
ton	ton	0.907 metric ton
lb	pound	0.453 kilogram
oz	ounce	28.349 grams

Metric Abbr.	Unit	Approximate U.S. Equivalent
	Length	
km	kilometer	0.62 mile
m	meter	39.37 inches *or* 1.09 yards
cm	centimeter	0.39 inch
mm	millimeter	0.04 inch
	Area	
ha	hectare	2.47 acres
	Volume/Capacity	
liter	liter	61.02 cubic inches *or* 1.057 quarts
ml	milliliter	0.06 cubic inch *or* 0.034 fluid ounce
cc	cubic centimeter	0.061 cubic inch *or* 0.035 fluid ounce
	Mass/Weight	
MT	metric ton	1.1 tons
kg	kilogram	2.205 pounds
g	gram	0.035 ounce
mg	milligram	3.5×10^{-5} ounce

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Contents

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Abstract

A study was conducted in order to investigate the incorporation of dehumidification into the curing cycle of flue-cured tobacco. Multiple cures of cultivar K326 flue-cured tobacco were made over three harvesting seasons. Tobacco from the same source and stalk position was cured in a barn coupled to a heat-pump-dehumidifier and, for comparison, in a conventional barn heated with an open flame propane furnace. In the heat-pump barn, dehumidification was applied during the lamina and stem drying phases, but not during the coloring and color-drying transition phases of the curing cycle. During successive cures of each season, modifications were made in the operation of the heat-pump barn in order to improve performance. A procedure for curing with dehumidification was developed. Dehumidification was found to automatically raise temperature and reduce humidity, causing a set in lamina color. Tobacco cured in the heat-pump barn was found to have at least comparable quality with that cured in the conventional barn as determined by standard chemical analyses and USDA grade. There was a significant reduction of Tobacco Specific Nitrosamines (TSNA) in the tobacco cured in the heat-pump barn as compared with tobacco conventionally cured. A short burst of high temperature heat was effective in finalizing stem drying in the heat-pump barn. Dehumidification constituted only 26.8 percent of the total energy use in the heat-pump barn.

Heat-Pump Dehumidification during the Curing of Flue-Cured Tobacco[1,2]

Bryan W. Maw, J. Michael Moore, Michael G. Stephenson, Paul E. Sumner[3]

Introduction

Curing is an essential part of flue-cured tobacco production. A curing schedule for bulk flue-cured tobacco has developed over the years that indicates temperature and humidity variations (figure 1, page 6). This was generated from earlier studies by Johnson *et al.* (1960) when the curing of a random arrangement of mechanically harvested leaves was being addressed. More recent publications further explain the cautions of curing and deviations thereof (Sumner and Moore, 1993; Sumner, 2001). Curing is considered an art as variations from the schedule are made according to experience.

Conventional curing is dependent upon heat being supplied to air circulating in the barn. Various levels of heat are required at different times throughout the cycle. Heat energizes chemical activity in the tobacco leaf; creates a potential that influences moisture movement within the tobacco leaf and stem; cooks the stem, causing fractures within the cellulose stem wall enabling moisture to migrate from the interior to the surface of the stem more easily and quickly; and modifies the drying capacity of the circulating air by lowering its relative humidity. Even though some heat is beneficial, the relative humidity may also be lowered and thus the drying capacity of the circulating air increased by dehumidifying the circulating air.

There are four recognizable phases in a flue-cured tobacco curing cycle (figure 1). These phases may be referred to as coloring or yellowing, color-drying transition or wilting, lamina drying or leaf drying, and stem drying. During the coloring phase, changes take place in the lamina (Todd, 1981), the most dramatic of which is the destruction of chlorophyll causing the characteristic bright yellow color of flue-cured tobacco. On purpose, the metabolic activity of the leaf is maintained until there is a conversion of starch to a complex series of sugars (Collins and Hawks, 1993). Starch levels may change from 25 percent down to very little, and sugars increase from about 10 percent up to 20 percent. A dry bulb temperature of around 38 degrees C (100 degrees F) is recommended for this phase. Fortunately, there is a direct relationship between coloring of the lamina and internal chemical conversion, so its process is visually evident. Coloring may take about two days, with complete chemical conversion taking a little longer. For that reason, the color-drying transition phase is initiated once coloring is complete.

During the color-drying transition phase (figure 1) the leaf chemistry continues to beneficially

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[2] The use of trade names in this publication does not imply an endorsement by the authors of the product named nor criticism of ones not mentioned.

[3] Bryan W. Maw, Associate Professor, Biological and Agricultural Engineering Department; J. Michael Moore, Professor, Cooperative Extension Service, Crop and Soil Science Department; Michael G. Stephenson, Agricultural Research Coordinator, Crop and Soil Sciences Department; and Paul E. Sumner, Senior Public Service Associate, Biological and Agricultural Engineering Department, University of Georgia.

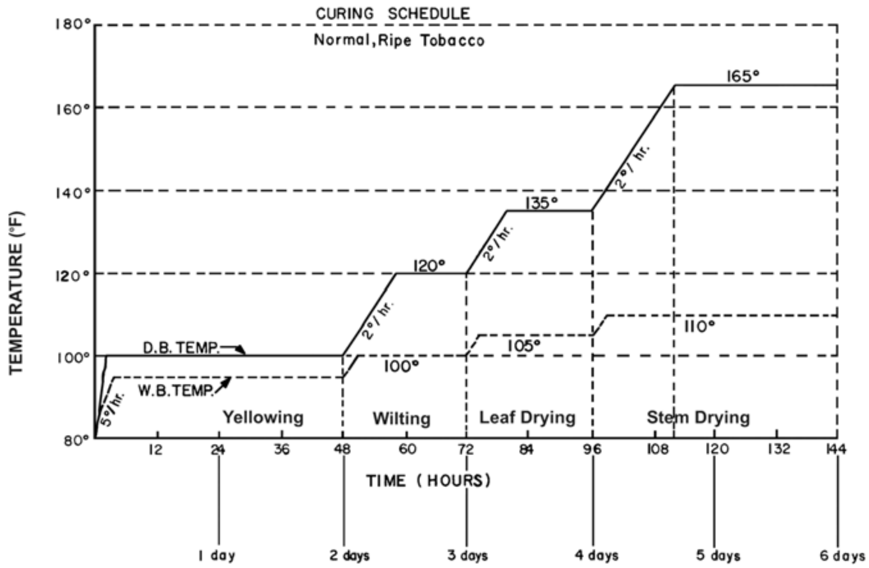

Figure 1. Curing schedule for mature, ripe tobacco (Watkins and Johnson, 1980).

change as the barn temperature is increased to around 49 degrees C (120 degrees F), at which temperature both the color and chemical composition of the leaf are set. Approximately 24 hours is recommended for this phase (Peele, 2000).

Even though approximately 30 percent of the total moisture may be removed during the first two phases(Collins and Hawks, 1983), drying begins in earnest during the lamina drying phase. Drying of the lamina is undertaken while the temperature of the circulating air is gradually increased to around 57 degrees C (135 degrees F) over approximately 24 hours. The stem, being more difficult to dry, then requires a higher temperature during the stem drying phase, with the air temperature being raised to around 74 degrees C (165 degrees F) over the next 12 hours. Drying during coloring is encouraged to prevent browning or scalding that may otherwise occur as a result of too high humidity and temperature in the barn. A further caution would be for stem drying temperatures not to exceed 77 degrees C (170 degrees F) in order to avoid the leaf being scorched to a red color. Applying heat to increase the drying capacity of the circulating air can be done as long as the internal air is not saturated. In order to prevent saturation of moisture in the air, a controlled portion of the internal air may be continuously exhausted and replaced with fresh air.

The above guidelines refer to variations in dry bulb temperatures. The relative humidity of the circulating air is also important. This is sometimes characterized by the wet bulb temperature in the barn. As well as for the dry bulb temperature, general guidelines exist for wet bulb temperatures during the curing cycle (figure 1). For example, a wet bulb temperature of at least 35 degrees C (95 degrees F) would ensure sufficient humidity in the barn for chemical conversion to take place without lamina drying to the extent that coloring and conversion can no longer take place. During the lamina and stem drying phases, a larger differential between dry and wet bulb temperatures may exist, once coloring and chemical conversion is complete, so as to enlarge the drying capacity of the air. Though wet bulb temperature is commonly used for determining and regulating the relative humidity of air in the barn, relative humidity may be directly measured or the dry bulb temperature of the exit air may be used as a guide to the relative humidity of the air inside the barn (Suggs and Ellington, 1994). This can alleviate difficulties of wick drying and contamination when operating at a high drying potential, often leading to automatic controllers over-ventilating the dryer and wasting fuel.

Sufficient airflow is required during the lamina drying phase to remove moisture and sufficient heat is required during the stem drying phase to finish drying the stem (Boyette, 2000). Bennett (1963) recommends an air flow of at least 40 $ft^3/min/ft^2$ of barn floor area at 0.5 in. static water pressure and 1,200 Btu of available heat capacity/ft^2 of floor space. Sumner and Cundiff (1983) report that 30 ft/min across the surface of the leaf will dry the leaf in an acceptable manner. It is desirable to have airflows 10 to 50 percent greater than the design minimum to compensate for variations in temperature and moisture in the barn. During the latter two phases, even with this airflow, the static pressure in the delivery plenum of a three-tier bulk rack barn may diminish to 0.1 to 0.3 in. WC (25-75 pa), whereas earlier in the cure, 0.8 to 1.0 inches of static water (in. WC) (200 - 300 pa) may be necessary to enable adequate airflow.

Energy use during curing traditionally includes electrical energy for driving the fan and petroleum or wood fuel for providing heat. The average heat to evaporate moisture during tobacco curing was reported as being 2588 kJ/kg (1113 Btu/lb) of uncured tobacco (Sumner and Cundiff, 1983), which translates to 0.116 L liquid petroleum/kg (0.0139 gal liquid petroleum/lb) of water removed. Assuming a water content of 90 percent for lower stalk tobacco the fuel consumption based upon water removal is then 1 L liquid petroleum/kg (0.12 gal liquid petroleum/lb) of marketed leaf and assuming a water content of 80 percent for upper stalk tobacco, the fuel consumption based upon water removal is then 0.42 L liquid petroleum/kg (0.05 gal liquid petroleum/lb) of marketable leaf.

The cost of curing is dependent not only upon the price of fuel but also upon burner efficiency. Sumner *et al.*(2001) reports the average fuel efficiency as being only 79 percent and so tuning burners, insulating barns and cycling of the fan and dryer can all influence the efficiency. Butts *et al.* (1983) reported annual savings averaging $338 per 156 rack barn when insulation was applied to tobacco barns. Maw *et al.*(1985) reported significant ($P<0.05$) annual savings averaging $234 per barn when cycling off the fan for 7.5 min and the furnace for 12.5 min per 30 min period, with no significant difference in duration of cure and tobacco quality. Savings have also been reported by Cundiff (1977, 1978) and Watkins (1976, 1977) for various periods of cycling. There is even some indication cycling may encourage drying. Some peanut dryers are equipped with cycling controllers (Blueline, 2000).

Heat has traditionally been provided to air circulating through the tobacco by means of an open flame burner in the tobacco barn. However, an understanding of nitrosamines in cured tobacco has lead to the retrofitting of barns to surround the open flame with a heat exchanger (Sumner *et al.,* 2002). Nitrosamines are organic compounds found in many natural products, including soil, water and food. Nitrosamines are referred to as free radicals and some are known to be carcinogens. The tobacco industry has been examining tobacco products for nitrosamines for some time (Smith, 1999) and tobacco specific nitrosamines (TSNA) are sometimes found in cured tobacco, though not usually in uncured tobacco. Once formed, the TSNA remain and are part of whatever the tobacco leaf becomes. Data presented by Peele *et al.* (1999) strongly supports the contention that direct-fired curing provides combustion by-products (*i.e.,* oxides of nitrogen) that contribute to the formation of TSNA during the flue-curing of tobacco. Direct-fired curing was shown to be the primary source of TSNA formation in flue-cured tobacco, significantly overshadowing microbial-mediated mechanisms.

Introducing dehumidification is another way whereby the efficiency of curing may be improved. By removing moisture from the circulating air, the capacity to remove moisture from the tobacco is enhanced. Technology, known as heat pipe technology (Advanced Dryer Systems, Gainesville, Fla.) is now available that increases the condensation of moisture from air that would otherwise be removed by an air conditioner condenser coil (figure 2). Heat pipes have been a recognized technology since before 1983 when Khanh Dinh founded Heat Pipe Technology, Inc. However, for exchanging heat from a source to a receiver, a primary patent was issued in 1986 (Dinh, 1999). By using the principles of heat transfer that occur as a result of a change of state of a fluid, heat pipes passively remove heat from warm air and transfer it to cool air. When combined with a conventional air conditioner, having cooling coils and a compressor, increased cooling and thus drying of the incoming air is possible as moisture is condensed from the air. The result is a high capacity dehumidifier (figure 2, page 8). According to searches of the literature, curing tobacco with this technology has not been attempted.

Objectives

The objective of this study was to examine the feasibility of introducing dehumidification of air circulating in the barn during curing of flue-cured

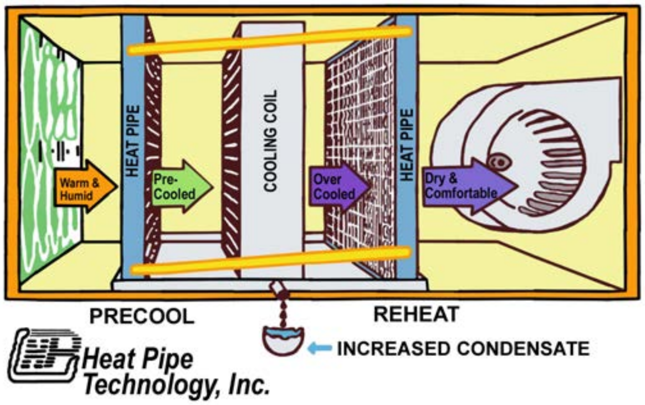

Figure 2. Diagram of the heat-pump-dehumidifier. (Dinh, 1999)

tobacco, with the intention of at least maintaining the quality of cured leaf as compared with conventional curing methods.

Materials and Methods

Since no prior experience existed in curing tobacco using dehumidification, this project progressed until, after three years, sufficient reportable knowledge had been accumulated. The procedure was developed from cure to cure with the intention of improving technique and tobacco quality. However, certain items were common to all cures and are specified for all cures over all years.

Flue-cured tobacco 'K326' was harvested from successive positions up the stalk during 1999-2001 and was cured using two comparative methods. Part of the tobacco was cured in a barn coupled to a heat-pump-dehumidifier and part conventionally cured in a second barn (table 1). The heat-pump-dehumidifier had the capability of dehumidi-fying air circulating through the tobacco barn to which it was coupled. Though the tobacco was taken from successive stalk positions, the similarity of tobacco from those positions was sufficient to evaluate changes in procedure.

Flue-cured tobacco quality is primarily determined during the coloring and color-drying transition phases. Since those conditions were not variables in the test, dehumidification was undertaken only during the lamina and stem drying phases. Nevertheless, the heat-pump-dehumidifier contained a fan and electrical heat strips which could be used to move and heat barn air at any phase of the cure. The heat strips were controlled with a remote temperature controller installed in the tobacco barn between the two levels of racks of tobacco.

Conventional curing followed the curing schedule shown in figure 1 with air being heated by an open flame liquid propane burner. At the time of the study, concern was being shown towards the accumulation of TSNA in tobacco leaves during curing as a result of NO_x accumulation. Part way through the study, commercial barns were being converted from having an open direct flame burner to having an indirect flame burner by way of a heat exchanger. However, for consistency throughout the study, conventional curing was considered as direct-firing, which then enabled additional benefits of heat-pump-dehumidification to be expressed in terms of TSNA reduction.

Table 1. Cures and duration of cures for tobacco cured by heat-pump and conventional barns, 1999-2001.

Cure	Barn type	Curing began 1999	Cure (h)	Curing began 2000	Cure (h)	Curing began 2001	Cure (h)
1	heat-pump	30 June	282	13 July	185	28 June	196
	conventional	30 June	282	14 July	159	28 June	141
2	heat-pump	14 July	192	21 July	310	11 July	187
	conventional	14 July	192	21 July	166	11 July	138
3	heat-pump	27 July	165	03 August	245	20 July	176
	conventional	27 July	142	03 August	136	20 July	139
4	heat-pump	4 August	130	14 August	151	30 July	162
	conventional	4 August	130	14 August	117	30 July	162
5	heat-pump	11 August	151			07 August	158
						07 August	114

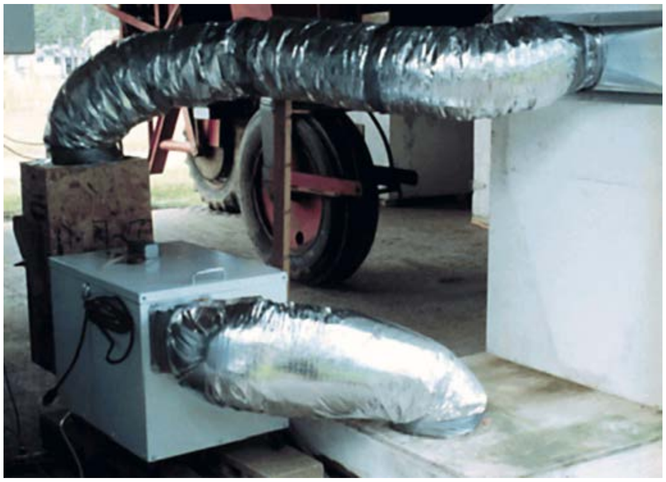

Figure 3. Heat-pump-dehumidifier coupled to the two-rack barn via flexible ducts.

1999: During the first year of the study, tobacco was cured in a small two rack barn. A heat-pump-dehumidifier (BKP 100, Advanced Drier Systems, Gainesville, Florida), built to incorporate the features of heat pipe technology and to maximize commodity drying with a minimum of energy, was coupled to an insulated two rack curing barn (heat-pump barn) by means of 15 cm (6 in.) diameter flexible insulated ducts (figure 3). A water trap was added to the condensate outlet pipe to ensure that dehumidified air did not leak from inside the heat-pump, nor ambient air be taken into the circulating barn air through the outlet pipe.

Five cures were conducted during the harvest season (table 1) with two racks of tobacco being cured on each occasion. Tobacco was also conventionally cured for each of the first four cures, there being insufficient tobacco available for the fifth conventional cure. Data collected and experience gained using the small barn paved the way for the successive two years of study.

Coloring and color-drying transitions phases were conducted by simply closing the small barn and allowing the temperature and humidity to establish their own levels within the barn. No forced fan movement or heating of the air was necessary.

At the beginning of the lamina drying phase of the first cure, the heat-pump-dehumidifier was operated in an open loop with fresh air being brought from outside and dehumidified before being blown into the barn. After five days into the drying phase of the first cure and in successive cures, the heat-pump-dehumidifier was operated in a closed loop with the air from inside the barn being dehumidified and re-circulated. In this way a higher internal air temperature and a lower relative humidity could be achieved than was the case taking in fresh ambient air. Heat was generated and accumulated in the barn when moisture was condensed out of the air, releasing latent heat of vaporization. The higher temperature proved to be beneficial both for lamina and for stem drying. By implementing changes to the procedure, successive cures took less time to complete than did the first cure.

2000 and 2001: A heat-pump-dehumidifier (DK 5 EL, Advanced Drier Systems, Gainesville, Florida) was coupled to an insulated 12-rack curing barn (heat-pump barn) (figure 4). Through dimensional analysis, it was understood that there would not be a linear relationship between the behavior of the 12 rack barn in comparison with the two rack barn of the previous year, however, a best attempt was made at designing the heat-pump-dehumidifier for use with a 12-rack barn. The outcome of the curing operation was dependent upon the chosen design. The heat-pump-dehumidifier was coupled to the heat-pump barn by means of insulated flexible ducts of diameter 30 cm (12 in.). The intake air to the barn was below the lower row of racks through a port in one of the double doors and the exhaust air from the barn through a port in the upper plenum of the barn above the upper racks of tobacco.

Figure 4. Conventional barn (left) beside the heat-pump barn (right) with coupled heat-pump-humidifier

Insulation was applied to the ducts and to exposed surfaces of the heat-pump-dehumidifier to conserve heat generated during the dehumidification process. For comparative purposes tobacco was conventionally cured in a second 12-rack curing barn. Both barns were insulated with 5 cm (2 in.) of polystyrene.

Four cures were conducted in 2000 and five in 2001 (table 1). During the coloring and color-drying transition phases a minimum airflow and air temperature was maintained in the heat-pump barn. Closed circuit air flow in the heat-pump barn was encouraged by means of the fan in the heat-pump-dehumidifier and the air was heated as it passed through strip heaters inside the heat-pump-dehumidifier. Since no moisture was being generated, as would otherwise occur under open flame combustion, a water mist of hollow cone nozzle capacity 12 L/h (3.1 gal/h) was sprayed as air re-entered the barn after circulating through the heat-pump in order to maintain a minimum level of humidity recommended for the first two phases (figure 1).

Since for the heat-pump barn the heat-pump-dehumidifier was coupled to a conventional style of barn, the barn was equipped with an internal fan formerly used to generate air circulation in the barn through the tobacco. Though the use of this fan was introduced into the procedure of curing with the heat-pump barn, when the fan was not being used, dampers were closed at the entrance and exit of the fan housing to prevent air from bypassing the tobacco during the coloring and color-drying transition phases as it traveled from the intake to exhaust ports, circulated by the fan in the heat-pump. Then, during the lamina and stem drying phases these dampers were opened and the internal fan put into operation. The additional air circulation during those phases was found to be beneficial to the rate of drying the lamina and stem.

To encourage the conclusion of stem-drying, high temperature heat was provided by the heat-pump-dehumidifier strip heaters to the circulating air for approximately 12 hours. Although, during high temperature heat, the thermostat was set on 77 degrees C (170 degrees F) because the heat strips were under capacity for the barn size, the heat-pump barn was able to only generate approximately 65 degrees C (150 degrees F). During high temperature heat, air circulation was changed from a closed to an open loop circuit, releasing heat-pump barn exhaust air to the atmosphere and admitting fresh atmospheric air for conditioning and supply to the barn. This decision was based upon finding the ambient atmosphere having a lower relative humidity than even that being generated through dehumidification inside the barn and based upon heat being generated through the dehumidification process being small compared with that applied from the strip heaters.

Chemical and TSNA analyses of cured tobacco

Analyses of alkaloids, total sugars, reducing sugars, chlorides and phosphates (PO_4) were conducted on samples of cured tobacco collected at the end of each cure. Analyses of TSNA were conducted on tobacco samples taken on each of three occasions for each cure: as the tobacco was being harvested; after the color-drying transition phase; and after stem drying. The samples, each filling a 7.5 L (2 gallon) capacity polyethylene bag, were stored in a freezer until they could be analyzed. A total of 90 samples were analyzed over the three years, 18 in 1999, 36 in 2000 and 40 in 2001. Analyses were conducted by the Research and Development Division of Brown and Williamson Tobacco Company, Macon, Georgia.

Grades and grade indices of cured tobacco

Four samples of cured tobacco per cure were collected following each cure. Grades were given to the samples of tobacco by USDA graders. Grade indices were subsequently given to these grades (Wernsman and Price, 1975).

Temperature and humidity inside the barn during curing

A data logger (Campbell 21X, Campbell Scientific, Utah) with sensor probes (models HMP 35 C-L and HMP 45 C-L) was used to record temperature and relative humidity throughout the cures with the exception of conventional cures 1-4 during the first season. The sensors were known to have a tolerance of + or -4 percent and to be most accurate within the range 10-90 percent rh and were known for moisture to saturate the filter on the sensor to give erroneous readings when being used in a saturated environment. Sensors were carefully positioned inside the barn in order to have a true indication of internal barn behavior. The internal below-tobacco sensor was placed above the floor but not directly inline with the incoming airflow. The internal barn above-tobacco sensor was placed in the stream of the exhaust vent air so as to measure the temperature and humidity of the air as it exited the barn on its way to be conditioned by the heat-pump-dehumidifier. The feed-back temperature sensor for the heat strips was placed through a hole in the door in between the two levels of racks and away from the internal door surface. A shaded sensor was used to measure the ambient conditions was placed under an open shed for the benefit of shade. Frequent visual observations of the temperature and relative humidity in each barn gave an indication of the condition of the tobacco inside the barn especially as to the extent of drying during the lamina and stem drying phases.

Moisture removed from the tobacco during curing

Even though during curing, solids losses do occur (Maw *et al.*, 1985), weight loss during the study was attributed to the extraction of moisture from the lamina and stem. During 2000 and 2001, tobacco in both the conventional and heat-pump 12 rack barns was weighed at intervals during the cure. The racks of tobacco were supported on a portable frame that could be suspended on a weigh scale (Martin Decker, B621C.0015K, Santa Ana, California) with the assistance of an electric hoist (Duff Norton, Charlotte, North Carolina). Subtracting the empty frame and rack tare weights of 482 kg for the conventional barn and 514 kg for the heat-pump barn, the net tobacco weight was determined. By weighing the tobacco during curing, progress of the drying process could be assessed.

Airflow in the barns

Airflow was measured between the racks and in the lower plenum during some of the cures in 2001 (series 1440 digital air velocity meter, Kurz Instruments Inc. Monterey, Calif.). The measurements were discontinued during high temperature heat.

Cycling of electrical power to the heat-pump barn

As a means of conserving electrical power without jeopardizing tobacco quality or time of drying, cycling of electrical power to the heat-pump-dehumidifier and internal barn fan was conducted using a time switch (model 21E213, Dayton Electrical Manufacturing Company, Chicago, Illinois). Power off times of 25 percent and 50 percent during each hour were tried during different cures. During the remainder of the cure, continuous power was provided to all electrical components. Continuous power was provided to the conventional barn throughout all cures as would be the case under conventional curing.

Energy used during curing

Propane gas used in the conventional barn was measured using an inline gas meter (Singer gas meter model AL425, American Meter Division) reading in gallons of liquid propane after converting from a volume of vapor to a volume of liquid where 36.2 ft^3 of vapor are equivalent to one gallon of liquid propane at 68 degrees F, calculated at 30 p.s.i. The electrical power used both in the conventional barn fan, the heat-pump barn internal fan and the heat-pump-dehumidifier was measured using separate watt hour meters (GE Watt hour meter CL200, 240v 3W) reading in kW·h.

Data analysis

Analyses were conducted using Proc MIXED (Littell *et al.*, 1996). Harvest seasons (years) were assumed to be random. Just as the number of cures varied from year to year, so did the number of samples. Years were considered as main blocks. Within each year, tobacco was harvested at successive positions up the stalk with each priming being split into two samples, one for each of the curing methods. From each cure, four samples of tobacco were taken for chemical analysis. This produced a split-split plot. Appropriate tests of effects were automatically conducted by the mixed models analysis.

Results and Discussion

It was an objective of the study that the quality of tobacco cured using dehumidification should be at least as good as that cured by the conventional method. Therefore unless the quality of tobacco was enhanced by using dehumidification, it was preferable for there to be no significant difference between methods. Accompanying graphs of temperature, humidity and moisture loss have been referenced to the day and time when dehumidification in the heat-pump barn was begun, hence negative days before and positive days after dehumidification began on the horizontal axis.

Tobacco quality as illustrated by the chemical analyses of the cured leaf

There was no significant difference between the analyses for tobacco cured by either method (table 2, page 13). Since cures appear in the main plot of the model, a more stringent test is required than for curing methods. They appear as a sub-plot in the model. Alkaloids (TA) were found to have means of 2.73 percent for the heat-pump and 2.51 percent for the conventional barn, being within suggested limits of 2.14-3.37 percent (Gaines *et al.,* 1983), generally increasing with stalk position or priming. Reducing sugars were found to have means of 13.6 percent for the heat-pump and 13.8 percent for the conventional barn, being slightly below the suggested limits of 15-22 percent (Gaines *et al.,* 1983), likewise, generally increasing with stalk position or priming. Total sugars were found to have means of 18.7 percent for the heat-pump and 19.4 percent for the conventional barn. Chlorine levels were similar at 0.37 percent for the heat-pump and 0.40 percent for the conventional barn and did not generally vary with successive cures. Phosphates were found to have means of 0.50 percent for the heat-pump and 0.49 percent for the conventional barn, above suggested limits of around 0.15 percent (Parker *et al.,*1993). The ratios of reducing sugars/total alkaloids were 4.98 for the heat-pump and 5.50 for the conventional barn, below limits of 6.5-8.5 suggested by Weybrew *et al.* (1983) or limits of around 6.4 as suggested by Gaines *et al.* (1983).

Chemical analyses were also conducted on samples of uncured tobacco during the last season. The values compared with those of the tobacco following curing. There was no significant (P<0.05) change in alkaloids, chlorides and phosphates whereas there was an increase in the sugars as a result of curing.

Tobacco quality as illustrated by the grade and grade index of the cured leaf

There was no significant (P<0.05) difference between the mean grade indices of tobacco cured by either method over all cures (table 3, page 13). Neither was there a difference between cures over all three seasons.

Color and color-drying transition phases and tobacco quality

It was necessary to make sure coloring was complete before enacting the dehumidifier because, once in operation, the color of the tobacco leaf became set. This was noticeable if there was any green color visible in places on the lamina. Electrical strip heat was applied to support the internal barn temperature at a minimum of 32 degrees C (90 degrees F) during the coloring and color-drying transition phases. Without heat, the internal barn temperature was found to dip to as low as 22 degrees C (71 degrees F) during the night time as a result of the natural diurnal ambient temperature fluctuations, thus reducing the rate of chemical activity in the leaf and elongating cure time. Since it has been shown that the overall quality of tobacco cured in the heat-pump barn was not significantly (P<0.01) different from tobacco cured in the conventional barn, it may be concluded that conditions for the coloring and color-drying transition phases in the heat-pump barn were adequate for coloring and chemical conversion as compared with the conventional barn. The temperature during coloring and the coloring-drying transition phases needed to be sufficient to encourage chemical conversions in the leaf but not so much as to cause too much drying of the leaf. Since the electrical strip heater produced no moisture in contrast with an open propane flame (1.25 gal of water per gal of L.P. gas), excessive drying as shown by green edges of the leaves took place at temperatures as high as 38 degrees C (100 degrees F) even with a mist of water applied to the intake air. An intake air temperature of 34 degrees C (94 degrees F) was found to be a suitable compromise of the different internal barn temperatures tried.

Lamina and stem drying phases and tobacco quality

Since it has been shown that there was no significant (P<0.01) difference between the quality of tobacco cured by either method so the variation in time and procedure throughout the study were not an influential factor on tobacco quality cured in the heat-pump barn. Drying of the lamina and veins within the lamina was easily accomplished with

Table 2. Chemical analyses (%) for alkaloids, reducing sugars, total sugars, chlorides and phosphates following curing in heat-pump and conventional barns, 1999-2001.

Cure	Barn Type	Alkaloids (%)	Reducing Sugars (%)	Total Sugars (%)	Chlorides (%)	Phosphates (%)
1	heat-pump	1.92 a[1]	11.2 a	17.6 a	0.39 a b	0.48 a
2	"	2.84 b	14.4 a	19.3 a	0.28 a	0.40 a
3	"	2.88 b	13.5 a	19.2 a	0.36 a b	0.50 a
4	"	2.84 b	15.0 a	19.2 a	0.35 a b	0.34 a
5	"	3.15 b	15.0 a	18.1 a	0.48 b	0.73 b
1	conventional	1.75 a	9.9 a	16.5 a	0.44 a b	0.51 b c
2	"	2.31 a b	14.8 b	23.9 b	0.37 a b	0.55 b c
3	"	2.39 b	13.7 a b	18.8 a b	0.37 a b	0.45 a b
4	"	2.99 c	13.7 a b	18.2 a	0.33 a	0.33 a
5	"	3.11 c	15.5 b	19.2 a b	0.51 b	0.65 c
L.S.D.		0.06	4.06	5.19	0.17	0.17
1	both	1.84 a	10.6 a	17.1 a	0.42 a b	0.49 b
2	"	2.57 b	14.6 b	21.6 b	0.33 a	0.47 b
3	"	2.63 b	13.6 b	19.0 a b	0.37 a	0.47 b
4	"	2.91 b c	14.4 b	18.7 a b	0.34 a	0.34 a
5	"	3.13 c	15.3 b	18.7 a b	0.50 b	0.69 c
L.S.D.		0.42	2.89	3.7	0.12	0.12
	heat pump	2.73 a	13.6 a	18.7 a	0.37 a	0.50 a
	conventional	2.51 a	13.8 a	19.4 a	0.40 a	0.49 a
L.S.D.		0.23	1.49	1.96	0.08	0.08

[1]Means separation done within heat-pump or conventional cures.
Means with same letters are not significantly different at $\boldsymbol{P}=0.05$.
N for analysis = 90, the total number of observations.

Table 3. Grade indices of tobacco as analyzed over all harvest seasons following curing in heat-pump and conventional barns, 1999-2001.

Cure	Number of Samples	Heat-pump Barn	Number of Samples	Conventional Barn	Mean
1	10	63.5	9	60.7	61.9 a
2	10	62.5	10	64.0	63.2 a
3	10	58.4	10	57.7	58.0 a
4	10	59.3	10	59.8	59.5 a
5	6	46.3	4	69.2	54.4 a
Mean		58.5 a		60.3 a	

Note: Years are assumed random and provide a source of error. The number of cures and thus the number of samples vary from year to year.
Means having the same letters are not significantly different at $\boldsymbol{P}=0.05$.
Interior LSD = 25.2; Cure LSD=17.82; Treatment LSD=11.27 (year x cure x treatment is the error term).

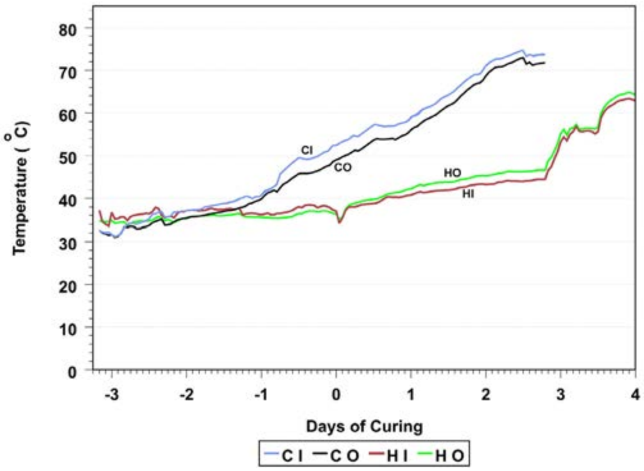

Figure 5. Average temperature of supply and exhaust air for both conventional and heat-pump barns. CI = conventional in; CO = conventional out; HI = heat-pump in; HO = heat-pump out.

dehumidification, especially as some drying naturally took place during the coloring and color-drying transition phases. The lamina drying phase usually took less than 24 hours to accomplish once dehumidification was underway, however, drying the stem took longer than for the lamina. Upper stalk leaves colored and dried more quickly than lower leaves. Even though there were variations for each cure as influenced by stalk position and climate, throughout the study the total cure time was reduced from 13 days, observed during the second cure in 2000 when curing was allowed to take as long as necessary using only dehumidification, to 6.5 days or less when high temperature heat was introduced during later developments of the curing guidelines.

Temperature inside the barn during curing

Typical curves of temperature variation for the supply and exhaust air of both conventional and heat-pump barns are given in figure 5. This curve was derived by averaging such curves from the fourth cure of 2000 along with all five cures of 2001 for the heat-pump barn and the four cures of harvest season 2000 along with the first cure of 2001 for the conventional barn. The cures were chosen according to the development of curing procedure for the heat-pump barn throughout the study and so represented the latest development. Likewise those of the conventional barn were chosen as being closest to the established conventional curing schedule.

The temperatures of conventional and heat-pump barns were similar during the coloring phase (figure 5). The temperature of the conventional barn began to rise during the color-drying transition and into the lamina and stem drying phases, similar to the guidelines of figure 1. The temperature of the heat-pump barn, however, continued as in the coloring phase throughout the color-drying transition phase.

At the beginning of the lamina drying phase (day=0) the dehumidifier was put in operation. As latent heat of vaporization was released during the condensation of moisture, the temperature of the heat-pump barn gradually increased. The combination of available heat and dehumidification was sufficient for rapid removal of moisture from the lamina within 24 h.

When high temperature heat was initiated to complete drying of the stem, the temperature rapidly increased. However, high barn temperatures were not satisfactorily sustained in the heat-pump barn at the level of the conventional barn because the electrical strip heat supply for high temperature heat was insufficient for the size of the barn and the amount of tobacco being cured. Having insufficient high temperature heat contributed to the longer duration of cure in the heat-pump barn as compared with the conventional barn.

The average ambient temperature over the harvest seasons was observed, yet the influence of the diurnal variation is more clearly shown when

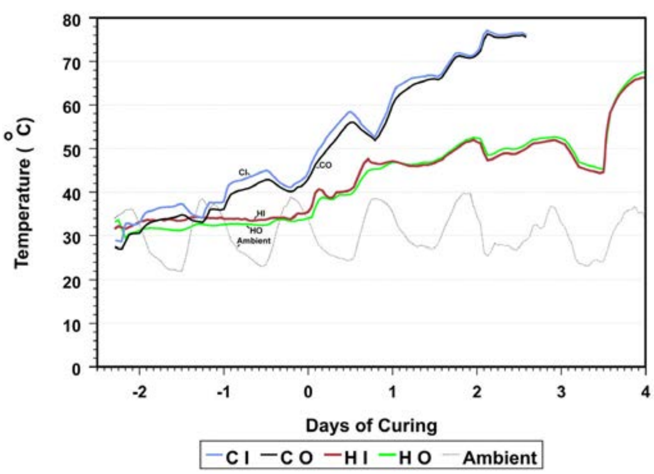

Figure 6. Influence of the diurnal variation in ambient temperature throughout a cure upon the temperature of the supply and exhaust air for both conventional and heat-pump barns. CI = conventional in; CO = conventional out; HI = heat-pump in; HO = heat-pump out.

considering the temperature variation during a single cure. For example, the fourth cure of harvest season 2000 is shown in figure 6 (page 14). An increase in ambient temperature during the day time caused a corresponding increase in the internal temperature of the heat-pump barn. However, the conventional barn had a phase shift lagging by about half a day. It is unknown why there was a difference in the reaction of the barns to the ambient temperature.

During the coloring and color-drying phases the input temperature of the heat-pump barn was higher than the exhaust temperature (Figure 5). Then, once the dehumidifier was in operation, there was an eventual inversion of temperature. This was common among all cures. The supply air was observed to be cooler when water was sprayed as a mist into the heat-pump barn than when it was not being sprayed.

Humidity inside the barn during curing

Typical curves of relative humidity variation for the supply and exhaust air of both conventional and heat-pump barns are given in figure 7 and were derived in the same way as the curves for temperature (figure 5).

In the conventional barn there remained throughout the cure a difference between the relative humidity of the incoming and exhaust air, diminishing towards stem drying. Following the coloring phase the relative humidity of both incoming and exhaust air steadily diminished. In the heat-pump barn the relative humidity of in-coming and

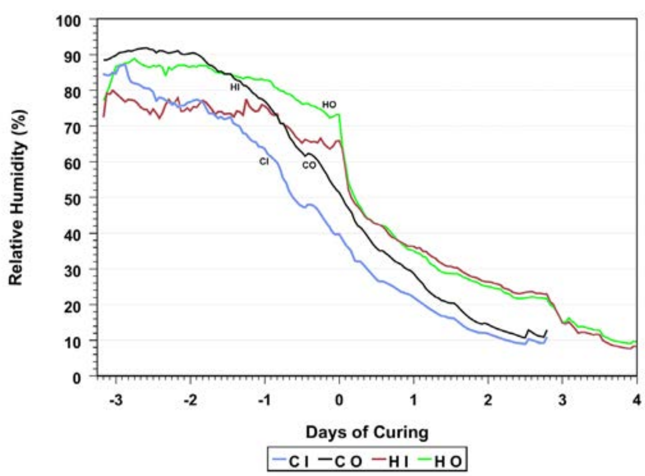

Figure 7. Average relative humidity of supply and exhaust air for both conventional and heat-pump barns. CI = conventional in; CO = conventional out; HI = heat-pump in; HO = heat-pump out.

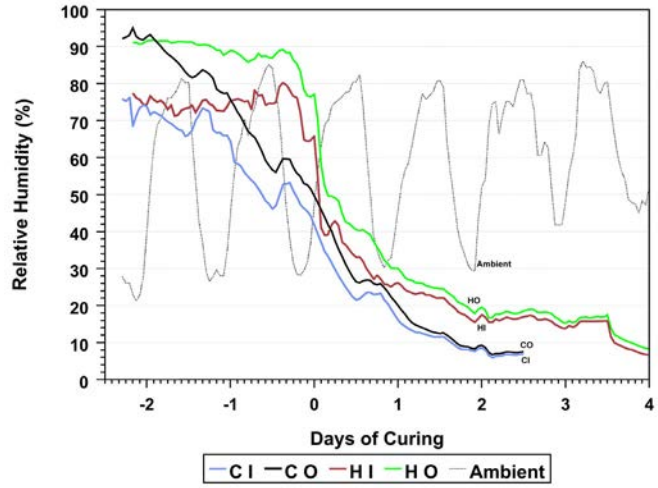

Figure 8. Influence of the diurnal variation in ambient relative humidity throughout a cure upon the relative humidity of the supply and exhaust air for both conventional and heat-pump barns. CI = conventional in; CO = conventional out; HI - heat-pump in; HO = heat-pump out.

exhaust air was similar to that of the conventional barn through the coloring phase and then was held higher than the conventional barn during the color-drying transition phase by spraying water into the intake air of the heat-pump barn in order to ensure completion of the chemical conversions in the leaf. Once the dehumidifier was switched on, the relative humidity was quickly reduced to levels similar to those of the conventional barn, after which the rates of reduction of relative humidity were similar for both barns, although the heat-pump barn took longer and benefitted from high temperature heat to reduce the relative humidity to that of the conventional barn within the last day.

The average ambient humidity was observed, but the influence of its diurnal variation is better illustrated in figure 8 as during the fourth cure of 2000. There was a half day lag in both barns. Furthermore, changes in internal temperature automatically influenced the relative humidity irrespective of the ambient conditions as for example during the introduction of high temperature heat when the humidity quickly dropped. On occasions, similar levels of humidity were found in both heat-pump and conventional barns even though the temperatures may have been different.

A relative humidity of around 90 percent in the exhaust air of the heat-pump barn was suitable for the coloring and color-drying transition phases. It proved to be adequate for leaf coloring and chemical conversion while at the same time allowing some drying of the lamina to take place. By the time the coloring phase had been completed there was sometimes sufficient water accumulated in the barn for the water mist sprayer operation to be unnecessary during the color-drying transition phase. Misting was therefore undertaken to maintain a relative humidity of around 90 percent.

The relative humidity quickly diminished during the lamina drying phase when the dehumidifier was switched on. In fact, once the laminar drying phase had begun, the relative humidity inside the heat-pump barn was allowed to fall as much and as rapidly as possible. Within a short time, the relative humidities of heat-pump and conventional barns would be similar regardless of the gradual reduction that had taken place in the conventional barn. It was helpful for excess water in the heat-pump barn to be cleared from the barn before beginning the drying phase. Opening the barn in order to remove internal fan dampers also enabled excess water from the mister to be cleared from the barn before dehumidification began, thus reducing the load on the dehumidifier and reducing the overall duration of cure.

Weight loss of tobacco during curing

The overall rate of moisture removal was similar for both conventional and heat-pump barns (figure 9). Even though the initial total weights of tobacco placed in the barn decreased throughout the season, average barn tobacco weights of uncured and cured tobacco (before being "put in order" by adding moisture to prevent shattering) are given in table 4 (page 17).

A comparison of moisture removal without high temperature heat as compared with that when high temperature heat was introduced into the heat-pump barn is given in figure 10 by plotting the in-barn tobacco weight curve for the second cure of 2000 having a duration of cure about 13 days, and that of the fourth cure of 2000 when the duration of cure was less than one week, comparable with conventional curing.

There were some variations in moisture loss during the cure. For example during the coloring and color-drying transition phases in 2000, the percentage changes of total moisture by weight were 41, 37, 44 and 39 percent for cures 1-4 of the heat-pump barn and 42, 40, 71 and 66 percent for cures 1-4 of the conventional barn. Such a difference between barns exhibits the way excessive lamina drying was discouraged in the heat-pump barn until dehumidification began whereas more extensive continual drying took place in the conventional barn.

As an example of percentage moisture content, during 2001 original wet basis moisture contents ranged from 86.88 to 81.08 percent for cures 1-5.

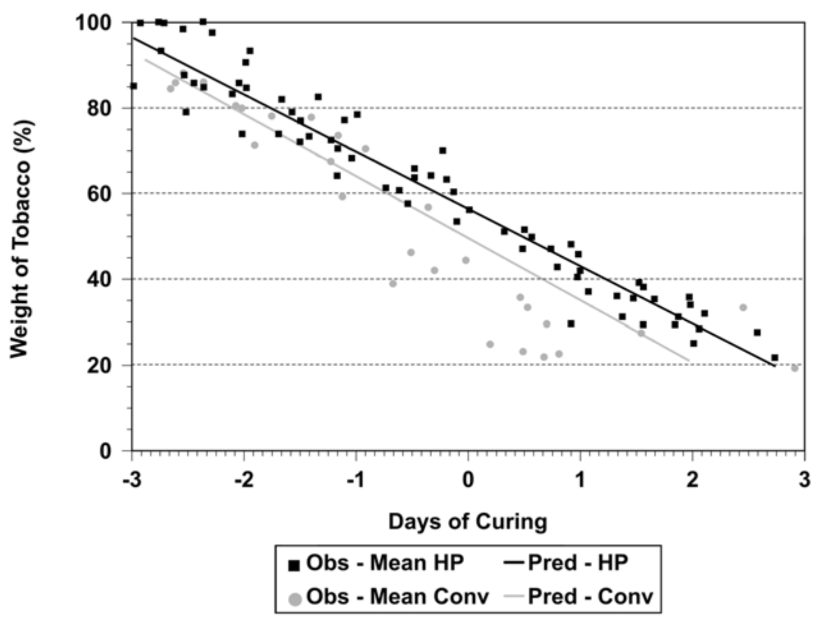

Figure 9. Regression lines representing the average rates of weight loss while curing in the heat-pump barn (HP) as compared with curing in the conventional barn (Conv).

Table 4. Average weight loss and energy use during curing of flue-cured tobacco in heat-pump and conventional barns.[1]

	Heat-Pump Barn				Weight of Tobacco		Conventional Barn					Weight of Tobacco	
	Elec Barn Fan kWh (%)	Heat Pmp kWh (%)	Total Power kWh (%)	Total Cost $	Uncured kg	Cured kg	Elec Barn Fan kWh (%)	Cost $	Propane Burner gal (%)	Cost $	Total Cost ($)	Uncured kg	Cured kg
Coloring	0 (0.0)	145 (23.8)	145 (23.8)	11.89			12 (21)	0.98	4 (12)	3.56	4.45		
Color-Drying trans.	0 (0.0)	62 (10.2)	62 (10.2)	5.08			10 (18)	0.82	5 (15)	4.45	5.27		
Lamina drying	7 (1.2)	41 (6.7)	48 (7.9)	3.94			16 (29)	1.31	12 (35)	10.68	11.99		
Stem drying	21 (3.4)	333 (54.7)	354 (58.1)	29.03			18 (32)	1.48	13 (38)	11.57	13.05		
Total	28 (4.6)	581 (95.4)	609 (100)	49.94	354	54	56 (100)	4.59	34 (100)	30.26	34.85	475	97
Cost per unit wt tobacco	based upon uncured wt				$0.14/kg ($0.06/lb)							$0.07/kg ($.03/lb)	
	based upon uncured wt.				$0.92/kg ($0.42/lb)							$0.36/kg ($.16/lb)	

[1] Cure 4 of 2000 with 1-5 of 2001 for heat-pump and cures 1-4 of 2000 with 1 of 2001 for conventional.

Final moisture contents, before the tobacco was put in order, were very small and were difficult to measure.

The rate at which condensate dripped from the trap pipe gave another indication of drying rate in the heat-pump barn when the dehumidifier was in operation since moisture had first to be released by the tobacco before it could be removed from the barn.

Airflow in the barns

Airflow at the entrance to the lower plenum from the internal fan was recorded as 33-200 m/min (110-650 ft/min) for both barns increasing throughout the cure as the tobacco became drier. This translated to 8-48 m^3/min (285-1688 ft^3/min) entering into the lower plenum of the barns and, when the barn floor area was taken into account, favorably compared with the recorded airflow of 3-12 m/min (10-40 ft/min) between the racks of tobacco.

In the heat-pump barn during the coloring and color-drying transition phases, a small airflow of 3 m/min (10 ft/min) was recorded through the tobacco, between the racks, driven solely by the fan in the heat-pump-dehumidifier. Then during the drying phases when the internal dampers had been removed and the internal barn fan put in operation, measurements were taken at different places in the barn. At the entrance to the lower plenum from the internal fan, airflow was recorded for both barn types as 110-650 ft/min (285-1688 ft^3/min according to the size of the duct) with a linear velocity through the tobacco between the racks of up to 40 ft/min, increasing throughout the cure as the tobacco became drier. During the lamina and stem drying phases airflow through the heat-pump was secondary to that of the barn because the heat-pump-dehumidifier was only conditioning the internal barn air and not entirely responsible for passing air through the tobacco.

Initiation of high temperature heat

Through the project, a threshold was established as to when high temperature heat could be introduced to be most beneficial. This was established as when relative humidity in the barn was below 20 percent, the slope of the weight loss curve was shallow with a barn tobacco weight of less than 600 kg and condensate production was reduced to a slow drip, although collection of condensate during drying was not an accurate indication of the amount of moisture being removed from the tobacco during that phase. It is possible that for upper stalk tobacco high temperature heat could have been introduced earlier than it was, as for example during the fourth cure of 2000 (figure 8), possibly reducing the overall cure time even further.

Duration of cure

The duration of cure (table 1) was a compilation of time spent on each of the four phases.

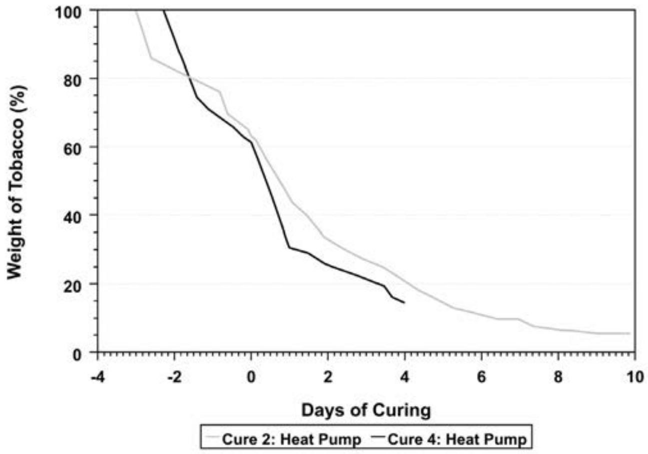

Figure 10. Weight loss of tobacco both while drying with only dehumidification and drying with the assistance of high heat.

Assuming that there was benefit in keeping the duration of cure to a minimum because it influences the required curing barn capacity for a crop, each phase was addressed in turn.

Time spent in the coloring phase was that required for the color of the lamina to change to the characteristic bright yellow. Temperature was known to influence chemical activity and 35 degrees C (95 degrees F) was adopted as a compromise between encouraging chemical activity and discouraging excessive drying at the tips of the leaves. Since the coloring phase could also be influenced by the degree of ripeness of the tobacco when it was harvested, it was beneficial to wait until the tobacco to be harvested was fully ripe. Leniency was given to considering coloring as being complete when there was still some green color in the veins and stem. These were known to dry to a black color and to be of less value than the main lamina. They are separated from the lamina during processing. The color-drying transition phase was kept to around 24 h to ensure completion of chemical activity in the lamina, influential in enhancing the quality of the tobacco. From figure 5 to figure 7, the first two phases took an average of just over three days.

Once the coloring and color-drying transition phases were complete and the tobacco quality established, the decision was made for there to be complete freedom to dry the leaf as quickly as possible. The rate of moisture extraction from the tobacco was influenced both by the rate at which moisture migrated to the surface of the leaf and the capacity of the dehumidification process. Although air-flow was considered to be adequate, the capacity of the heat-pump-dehumidifier could have been increased to the benefit of the operation. Lamina drying was sometimes observed to take 24 hours or less, depending upon the position on the stalk from which the leaf was harvested, being less for upper leaves.

In order to keep the expense of adding high temper-ature heat to a minimum and to ensure lamina drying to be complete the decision was made to wait until the relative humidity in the upper plenum of the heat-pump barn had dropped to around 20 percent before adding high temperature heat. From figure 7, this time averaged just under three days. The addition of high temperature heat was arranged to take place well into the stem drying phase and was meant to finally cook the stem in order to fracture the cell walls and thus release moisture trapped inside the stem. From figure 7, high temperature heat was added for an average of just over one day and could have been reduced if the capacity of the heat strips had been satisfactory in order to raise the tem-perature to the required 74 degrees C (165 degrees F). In fact, during the fifth cure of 2001, high temperature heat was begun after 2 days and 18 hours of drying and was undertaken for only 8 hours.

From the study, the average duration of cure for the heat-pump barn totaled approximately seven days, compared with approximately six days for the conventional barn. There is room for refining the design and operation of the heat-pump-dehumidifier and heat-pump barn, so possibly reducing the duration of cure for the heat-pump barn to at least equal or even less than that for conventional curing. Once again during the fifth cure of 2001, even using the equipment on hand, refinements reduced the total duration of cure to 6 days and 2 hours, though this was for upper stalk tobacco.

TSNA in tobacco during curing

Analyses taken of uncured tobacco proved that the levels of nitrosamines (TSNA) were below the limits of quantification (BLQ) of 0.025 ppm and so are not included in the analysis (Table 5, page 19). Likewise 89 percent of the TSNA values for cured tobacco from the heat-pump barn were below the limits of quantification. All values of TSNA for the conventional barn were above the limits of quantification. For those BLQ values of TSNA from the heat pump

Table 5. Means of TSNA (ppm) as recorded for tobacco cured using a heat-pump-dehumidifier in comparison with tobacco cured using an open flame furnace, 1999-2001.

Stalk Position	Curing Method		Average
	heat-pump barn	conventional	
1	0.189 a	0.839 a	0.514 a b
2	0.103 a	0.751 a	0.427 a
3	0.083 a	0.850 a	0.466 a
4	0.076 a	1.105 b	0.590 b
5	0.088 a	0.865 a	0.476 a
L.S.D.	0.421	0.421	0.298
Average	0.108 a	0.882 b	0.486
L.S.D.	0.170	0.170	

Means with same letters are not significantly different at $P=0.05$.
N for analysis=90, the total number of observations.

barn an arbitrary value of 0.0125 ppm was inserted for purposes of the analysis, 0.0125 ppm being midway between 0 and 0.025 ppm. Following curing, over all stalk positions the TSNA levels were significantly ($P<0.01$) lower in tobacco cured in the heat-pump barn than for tobacco cured in the conventional barn with means of <0.108 ppm compared with 0.882 ppm. Even 0.882 ppm for the conventional was low compared with TSNA values sometimes found for conventionally cured tobacco (Personal communication, Brown and Williamson analysis laboratory).

Examining the TSNA by stalk position for the different barns, there were no significant differences ($P<0.01$) between the TSNA of tobacco at the different stalk positions for the heat-pump barn, with all positions having very low levels of TSNA (Table 5). The same generally applied to the TSNA of tobacco from the conventional barn, but there appeared a trend toward higher levels of TSNA for middle to upper stalk tobacco than for tobacco from the lower positions. Tobacco from the lowest stalk position had a moderately high level of TSNA, however, sometimes these “sand lugs” are discarded and so are not a part of the total tobacco cured.

The accumulation of TSNA are known to be formed by living microbes and be time dependent, therefore it was an intention of the study to rapidly dry the lamina and stem once the coloring and color-drying transition phases were complete, thus minimizing the duration of cure and the likelihood of TSNA accumulation. By sampling tobacco at stages throughout the cure it was shown that differences between TSNA in heat-pump and conventionally cured tobacco arose following rather than before the color-drying transition phase. There were averages of 0.0299 ppm for heat pump and 0.0239 ppm for conventionally cured tobacco immediately following the color-drying transition phase, but averages of 0.108 ppm for heat pump and 0.882 ppm for conventionally cured tobacco following lamina and stem drying.

Electrical power cycling and tobacco quality

Cycling was administered to only the heat-pump barn. Cycling controlled the internal barn fan, the heat-pump-dehumidifier fan, heat strips and compressor. During 2000, cycling was introduced on the fourth cure, with a 25 percent setting in operation (measured to have 12 minutes ‘off’ during an hour) continuing through high temperature heat. During 2001, cycling was conducted on all cures, beginning in the first cure with a 25 percent setting and then in subsequent cures with a 50 percent setting. Cycling was conducted throughout both of the drying phases, during the first cure, but was discontinued during high temperature heat on subsequent cures in order to see if the internal barn temperature could be held closer to the required temperature of 77 degrees C (170 degrees F). As it was, the barn temperature was not noticeably higher with out cycling as compared with cycling.

Since it has been shown that the overall quality of tobacco cured in the heat-pump barn was not significantly (***P***<0.01) different from tobacco cured in the conventional barn, it may be concluded that cycling was not detrimental to tobacco quality, as given by the grade and chemical analyses (tables 1 and 2).

Cycling did not noticeably reduce the rate of moisture loss (figure 11). In fact, observations indicated there may be some relaxation and thus encouragement of moisture migration in the lamina and stem during the stopped time of cycling. During this time, the internal barn relative humidity would rise as much as 10 percent or more, even with little change in temperature, indicating that moisture was being released from the tobacco into the stagnant air of the heat-pump barn. Insufficient data was available for the calculation of accurate fuel savings as a result of cycling in this study.

Energy used during curing

As a means of economically comparing the energy used during curing by either method, the amount of electricity and propane used was converted to a cost based upon rates mid way through the study of \$0.082/kWh (Colquitt EMC quote August 29, 2000) for electricity and \$0.89/gal (Webb Bro. Propane, quote August 29, 2000, where 1 gal=36.2 ft^3 at 68 degrees F) for propane. The average value per cure was that derived from the fourth cure of 2000 along with all five cures of 2001 for the heat-pump barn and the four cures of harvest season 2000 along with the first cure of 2001 for the conventional barn. The cures were chosen according to the development of the curing procedure for the heat-pump barn throughout the study and so represented the latest development. Those of the conventional barn were chosen as being closest to the established conventional curing schedule.

From table 4, initial comparisons indicate that at the prescribed costs of electricity and liquid propane, the cost of curing tobacco in the heat-pump barn was twice that of curing in the conventional barn, being \$0.14/kg (\$0.05/lb) and \$0.07/kg (\$0.03/lb) of uncured tobacco.

Similar comparisons occurred for the cured tobacco. However, further examination of the components of the electrical energy use in the heat-pump barn, enabled the energy use of dehumidification alone to be calculated. The influence of dehumidification on total energy use was first examined during the lamina drying phase where dehumidification was known to be without strip-heat. Though the internal barn fan was operating at this time, it was monitored by a

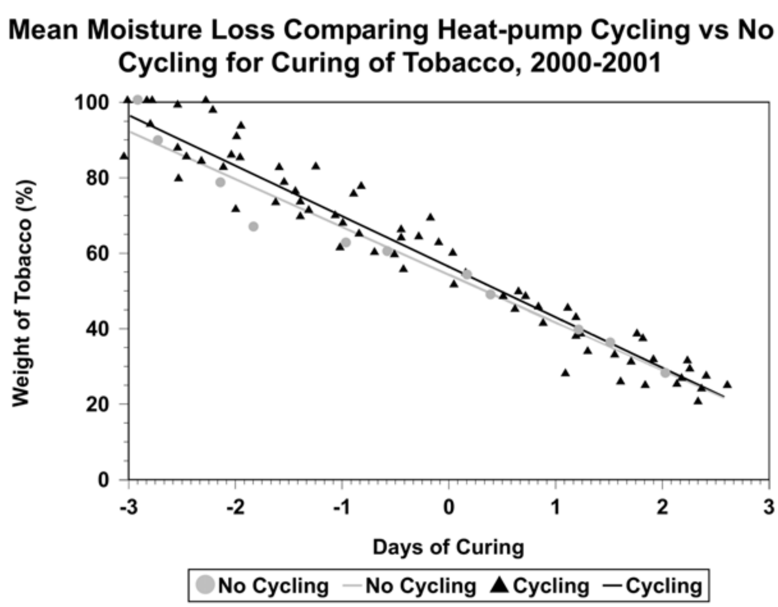

Figure 11. Comparison of weight change during curing while cycling as compared with curing with no cycling using regression lines through the plotted means.

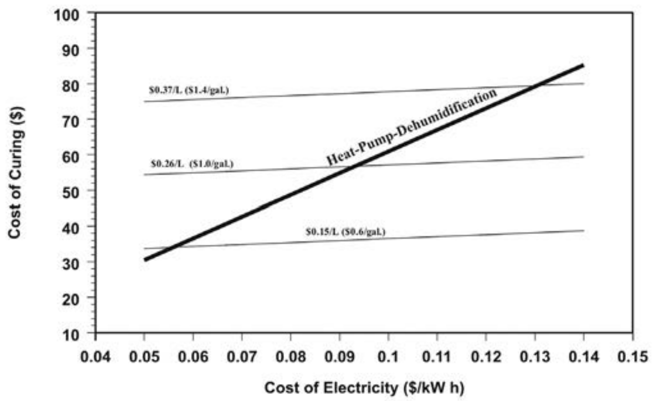

Figure 12. Determining the break-even point for using either heat-pump-dehumidification or conventional curing according to the price of fuel.

separate electrical power meter. It was understood that the small heat-pump fan was in operation any time the heat-pump was running whether for strip heat, dehumidification or both. During the lamina drying phase, the heat-pump used 6.7 percent of the total electricity (table 5) and was known to be of duration 24 h. From this basis the influence of dehumidification on the total electrical power use was calculated, because from figure 5 lamina drying and stem drying together had a duration of 96 h or 26.8 percent. The remaining energy use was for internal barn fan (4.6 percent) and strip heat. Strip heat therefore constituted 68.6 percent of the total energy use and yet strip heat was only used to maintain a minimum temperature during the coloring phase (23.8 percent) and the color-drying transition phase (10.2 percent) and then provide high temperature heat at the end of the stem drying phase (34.6 percent). Percentages are given to qualify the absolute energy values because the amounts were specific to the barn and heat-pump used and may not be applicable to other barns.

Operation of the dehumidifier was only 26.8 percent of the total energy use. This related to \$0.038/kg (\$0.02/lb) of uncured tobacco and \$0.25/kg (\$.11/lb) of cured tobacco. Dehumidification was therefore an economical component of curing. If a less expensive form of additional heat could have been provided, this could have been combined with dehumidification to provide a truly economical package for curing flue-cured tobacco.

Nevertheless, costs are relative to one another. Figure 12 gives an indication of the relative costs of each method given a change in fuel prices. The intersection of conventional curing using propane plus electricity with heat-pump curing using only electricity can be examined for different prices of propane or electricity. For example, for propane at \$0.89/gal, the break-even price for electricity would be about \$0.05/kW·h. On the other hand, if propane changed to \$1.50/gal, then an electricity price of \$0.11 would be competitive. This variable running cost analysis does not take into account the fixed costs of capital equipment, nor a variation in the efficiency of either curing method. The introduction of high temperature heat at the end of a cure to finalize stem drying effectively shortened the cure time and was economical compared with the extensive time taken without high temperature heat.

Guidelines for curing with a heat-pump-dehumidifier

The following guidelines were developed for curing flue-cured tobacco with the aid of a heat-pump-dehumidifier.

a) **Coloring phase.** Fill barn with fully ripe tobac-co and close internal fan dampers. Switch on heat-pump without the dehumidifier running. Set the heat-pump auxiliary heater to 35 degrees C (95 degrees F). Spray water mist into the incoming barn air in order to maintain a relative humidity in the barn of approximately 90 percent. Observe color change with a mini-mum disturbance of the humidity inside the barn until coloring is complete.

b) **Color-drying transition phase.** Continue the previous conditions another 24 hours with the exception of the water spray being continued or discontinued according to the need for moisture required in the barn to maintain the relative humidity in the barn around 90 percent.

c) **Lamina drying phase.** Open the internal heat-pump barn dampers, allowing the internal barn fan to be in operation. Switch on the heat-pump-dehumidifier with air in a closed loop between the barn and the heat-pump-dehumidifier. Cycle both barn fan and heat-pump-dehumidifier operations up to 50 percent of the time.

d) **Stem drying phase.** When the upper plenum relative humidity in the barn has been reduced to below 20 percent, choose an early morning to apply auxiliary heat to generate an internal barn temperature of 77 degrees C (170 degrees F) for 12 hours or until all stems are dry. When ambient conditions are more favorable than those inside the barn, change from a closed to an open loop of air circulation, admitting ambient outside fresh air through the heat-pump-dehumidifier for dehumidification before being sent to the heat-pump barn.

Summary and Conclusions

♦ Based upon experience from one harvest season to the next, multiple cures of flue-cured tobacco, of cultivar K326, were made first in a two rack barn and then in a 12 rack barn during the two subsequent harvest seasons, to investigate the possibility of incorporating dehumidification into the curing cycle of flue-cured tobacco using a heat-pump-dehumidifier coupled to the barns. For comparison, tobacco from the same source and stalk position was also cured in a conventional barn with an open flame propane furnace. During successive cures, modifications were made in the operation of the heat-pump-dehumidifier and barns to improve performance and tobacco quality, to reduce energy consumption and duration of cure. Performance was assessed in terms of standard tobacco chemical analyses, USDA grade, TSNA and energy use. A procedure for curing with dehumidification was developed.

♦ Curing in the heat-pump barn was divided into four phases: coloring, color-drying transition, lamina drying and stem drying. Since tobacco quality is determined by the first two phases, conditions during those phases resembled those of the conventional barn and were not a variable in the study.

♦ Heat was provided in order to maintain a minimum internal barn temperature. Water mist was sprayed into the intake air in order to maintain a minimum internal barn relative humidity during the coloring and color-drying transition phases. Without a minimum temperature and humidity, tobacco coloring was found to be slow and sometimes incomplete.

♦ Coloring was allowed to take as long as necessary, usually around two days, but the color-drying transition phase was held for 24 hours once coloring was known to be complete. Depending upon the observed relative humidity in the heat-pump barn, sometimes the water mist was not required during the color-drying transition phase.

♦ Dehumidification was not begun until the com-pletion of both the coloring and color-drying transition phases since the initiation of dehumidification raised the temperature and reduced the humidity to the extent of setting leaf color and reducing the likelihood of further chemical changes within the leaf.

♦ With the assumption that tobacco quality was established during the coloring and color-drying transition phases, drying of the lamina and stem were encouraged to take place as quickly as possible. In so doing, energy consumption was reduced, cure time was reduced and the likelihood of TSNA generation kept to a minimum.

♦ Whereas a low airflow across the tobacco of 3 m/min (10 ft/min) generated by the small fan in the heat-pump was sufficient during the coloring and color-drying transition phases, a higher air-flow across the tobacco of 12 m/min (40 ft/min) was beneficial during drying. Increasing air circulation during the lamina and stem drying phases by means of the internal barn fan, provided the necessary additional air circulation. During those phases the heat-pump then acted as a conditioner for air inside the barn using a small airflow without the heat-pump becoming overloaded from a high airflow.

♦ Adding high temperature heat to the heat-pump barn during the stem drying phase enabled the cure to be quickly curtailed. A judgment of when to switch on the high temperature heat was determined by monitoring the weight loss of tobacco and thus the rate of extraction of moisture by the dehumidifier, by monitoring internal barn relative humidity, and by monitoring the rate of condensate emission during curing in the heat-pump barn.

♦ It was beneficial to begin operation of high temperature heat during the stem drying phase at the beginning of the increase in daytime temperatures in order to reduce the load on the electrical strip heater. Following high temperature heat, tobacco was more easily brought "in order" during the night. Switching off the barn in the late evening and slightly opening the main doors to the barn allowed air loaded moisture from outside the barn to enter and be absorbed by the tobacco leaves while they were still warm. A greater heating capacity than was available would have been beneficial for the amount of tobacco being cured in order to keep the requirement for high temperature heat and the termination of stem drying to under 12 hours.

♦ During the coloring and color-drying transition phase, in order to contain the humidity, and during the lamina-drying phase in order to contain the generated heat of vaporization, a closed-loop circuit was necessary. However, during the high temperature heat stage of stem drying, while dehumidification was in operation, an open-loop of air circulation was preferable, allowing the exhaustion of barn air and intake of ambient air. A beneficial addition could have been a heat pipe that could have passively reclaimed and trans-ferred heat from the exhaust to intake air. Likewise heat could have been reclaimed from the external condenser coil of the heat-pump for use inside the heat-pump barn.

♦ Heat was applied during the coloring, color-drying transition and stem drying phases by means of electrical resistance heat-strips, since this source was available and did not encourage the growth of TSNA. In a commercial application the source of heat could vary according to the economics of available energy. A heat-pump-dehumidifier coupled with a propane fired heat exchanger could be one such combination.

♦ Cycling electrical power at the heat-pump barn during the drying phases was beneficial in saving energy without producing detrimental effects on tobacco quality and drying rate. Accurate savings in electricity were, however, not easy to document because there were uncontrolled variables such as tobacco stalk position and cure time compounding the results. A cyclical change in vapor pressure and temperature may have a positive effect on moisture migration within and from the lamina and stem beyond the obvious benefits of saving energy. Cycling could possibly have been implemented during the coloring and color-drying transition phases for the heat-pump fan and electrical strip-heater.

♦ In order to be acceptable, tobacco cured with dehumidification needed to be of a quality at least equal to that of conventionally cured tobacco. Since curing method had no significant effect on leaf chemistry or U.S.D.A. grade, the quality of tobacco cured in the heat-pump barn was no less than that cured in the conventional barn.

♦ There was a significant reduction of TSNA in the tobacco cured in the heat-pump barn as compared with tobacco conventionally cured with open flame propane heat. An indication of TSNA accumulation during curing was given.

♦ The costs of energy for curing tobacco in the heat-pump barn were favorable as compared with the conventional barn under current energy expenses and the effect of varying prices of electricity and propane were compared. Future adoption would depend upon the relative costs of electricity and propane. Nevertheless, dehumidification used only 26.8 percent of the total electricity in the heat-pump barn.

♦ A curing schedule was developed using dehumidification that was simple to enact when guidelines were followed. There was little opportunity for guesswork and the schedule could be used by a person not having curing experience.

♦ This study has provided exposure to new curing technology. As old tobacco barns are retired and new ones required, as there is a change in the economics of available energy, so will come the need for technology to meet the needs of the day. In conjunction with fully ripe tobacco and a tight barn there is potential for a curing schedule that is simple, maintains tobacco quality, keeps fuel consumption to a minimum, is short in overall cure time, and maintains TSNA at a low level. This study paves the way for the commercial development of concepts presented.

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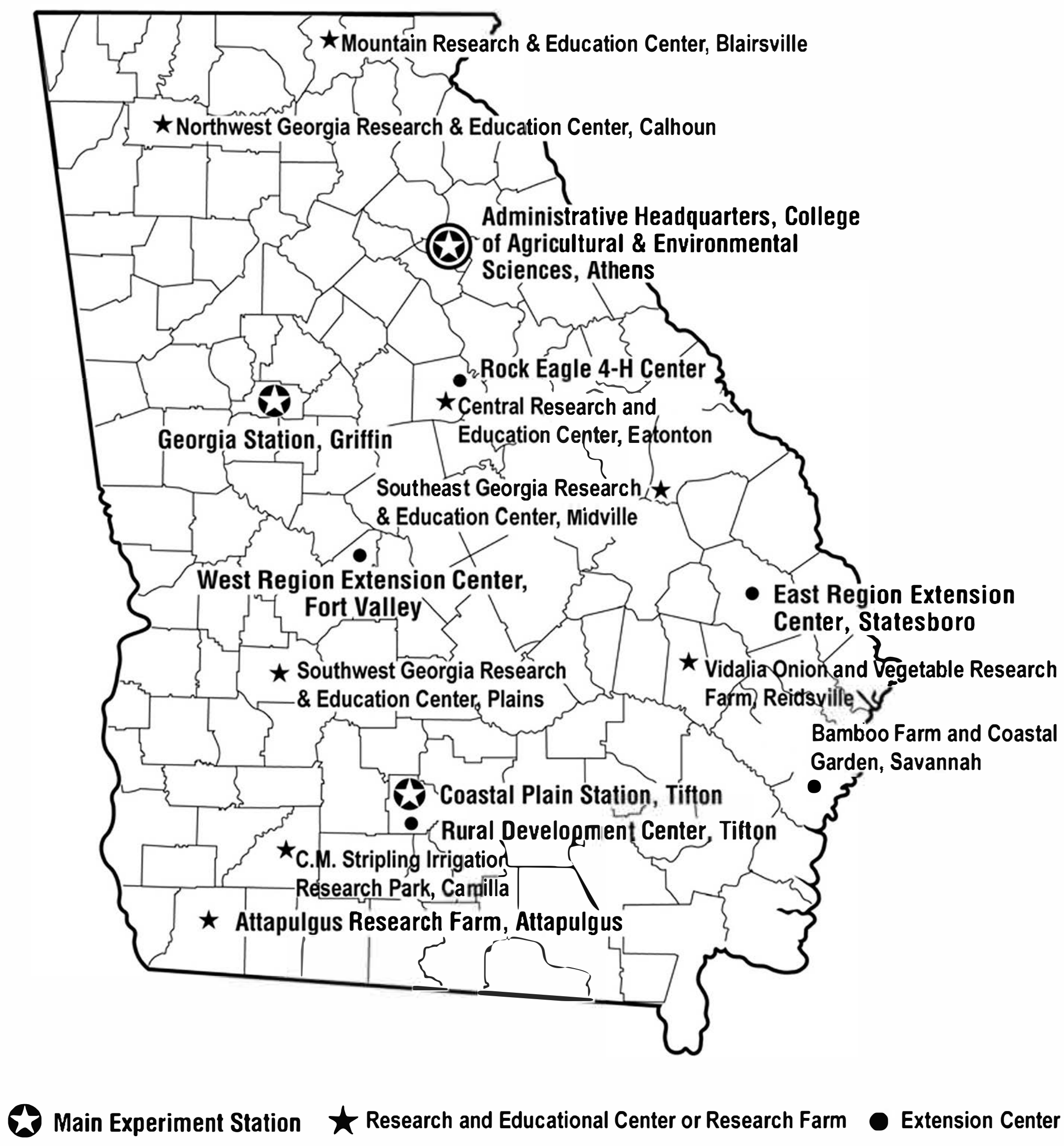

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