ABSTRACT

BATTEN, BRANDON DOUGLAS. Use of Variable Frequency Drives for Energy Savings in Curing Tobacco. (Under the direction of Michael D. Boyette.)

Curing costs remain one of the top three expenses for farmers involved in flue-cured tobacco production. Nearly all research in the area of improving curing efficiency and reducing energy use has been associated with reducing fuel use rather than with the electricity required to power the barn fan. A variable frequency drive (VFD) was implemented on tobacco barns in order to reduce the fan speed during the cure, thus reducing electricity consumption. Research was conducted at four locations in North Carolina with cooperating farmers to develop a fan speed reduction schedule in order to determine the potential savings associated with fan speed reduction. Locations included single and three phase power sources, box and rack-style barns, and tube axial and centrifugal style fans. Fan speeds were reduced during the leaf and stem drying phases of the cure by 5 to 15 percent in varying increments as the curing season progressed. Two identical barns were utilized at each location in order to compare electricity and propane (LP) or natural gas consumption, and heat exchanger surface. Electricity savings for tube axial fans ranged from 2 to 16 percent of the total electricity used as compared to the barn with no fan speed reduction. Maximum savings occurred when the fan speed reduction was the greatest and earlier in the cure. No decrease in tobacco quality or increase in curing time was observed. The centrifugal fan did not produce any savings attributable to the operation of the variable frequency drive.

Use of Variable Frequency Drives for Energy Savings in Curing Tobacco

by
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DEDICATION

I would like to dedicate this thesis to my family for believing in me no matter what and for always pushing me to chase my dreams, to mom and daddy for understanding the hard times, celebrating the good times, and picking me up and dusting me off when I stumbled, and to my grandparents for loving me unconditionally. A fellow just can't ask for much more than that.

Some men see things as they are and ask why. Others dream things that never were and ask why not.

~ George Bernard Shaw

BIOGRAPHY

Brandon Douglas Batten was born on November 26, 1985 in Goldsboro, North Carolina to parents Doug and Teresa Batten. Brandon is the older of two children. Brandon was raised on the family farm in the Strickland Crossroads community of southern Johnston County which grows tobacco, soybeans, small grains, hay and cattle. Brandon's love for agriculture was instilled at an early age as he spent countless hours on the farm with his father, his Uncle Steve and his Grandpa Toby. Brandon attended South Johnston High School where he was actively involved in the FFA, holding various offices at the chapter and federation levels. Brandon was also extensively involved in the county 4-H club, showing market hogs from the age of 5. Brandon enrolled at North Carolina State University for his undergraduate degree in Biological and Agricultural Engineering concentrating in agricultural engineering in 2004. While an undergraduate, Brandon was actively involved in the department's student branch of the American Society for Agricultural and Biological Engineers as well as the Quarter Scale tractor design team. Brandon graduated in 2008 and immediately enrolled in the Master's program for the same degree under the direction of Dr. Michael Boyette conducting energy research on flue-cured tobacco barns. Upon completion of his Master's program, Brandon intends to return home to continue the family's farming operation.

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1. INTRODUCTION

Curing flue-cured tobacco is both a drying process and a chemical process. During the cure, the leaf is dried from approximately 85% moisture to essentially zero percent at the end of the cure. In addition to the drying of the leaf, chemical changes in the leaf convert starches to sugars giving the process its name of curing rather than drying (Tso, 1972). This process was discovered around 1839 in the piedmont of southern Virginia. Tobacco originally was cured in stick barns and the burners were fired by hand. Stick barns were barns of wooden construction, with most being roughly 16 feet square and 16 feet tall. Tobacco was strung onto sticks with all leaves oriented the same way. These sticks were then hung in the barn four to six tiers high. Early flue-cured barns were fueled by wood in a rock or brick flue running along the floor of the barn. Later, metal flues were used to transfer the heat, thus the name flue-cured tobacco. During this labor intensive process, farmers would add wood to the fire as needed in order to increase the temperature. When more heat was required, more wood was added at a faster rate. Sliding panel vents on the barn were also adjusted as needed to provide appropriate fresh air ventilation through the barn.

Since the development of bulk curing in the Department of Biological and Agricultural Engineering at North Carolina State University in the late 1950s, tobacco has been cured primarily in bulk containers with widespread acceptance coming in the 1970s (Sykes, 2008). Indirect firing from gas fired burners using heat exchangers provides the heat required for curing. These burners primarily use liquid propane (LP) or natural gas, with a few growers still using fuel oil burners, and the firing rate is set according to the manufacturer's recommendations, but typically range from 350,000 to 500,000 BTUs per hour (Ellington 2007). A graph showing the typical heat requirement trend over time for a cure is shown in Figure 1-1. The heat requirement is greatest during the leaf-drying phase of the cure. A typical curing schedule for mature, ripe tobacco is shown in Figure 1-2. The yellowing phase is the portion from 0 to about 48 hours into the cure with temperatures around 105 degrees Fahrenheit. The leaf-drying phase is typically from 48 to 120 hours where the temperature is increased from 105 degrees to 145 degrees Fahrenheit. The stem-drying phase is the final phase occurring from 120 hours until the end of the cure where the temperature is increase to 165 degrees Fahrenheit. Forced air ventilation is provided by a fan, typically powered with a 7.5 to 10 horsepower electric motor that runs continuously throughout the curing process. A mixture of fresh air is pulled in through dampers and return air is pulled from inside the barn feeding the fan. Electricity only accounts for 10 to 15 percent of the total energy required to cure a barn of tobacco but accounts for approximately 20 to 25 percent of the cost of curing the same barn depending on motor size, length of cure, and the cost of electricity and curing fuel (Ellington, 2006).

1.1 Fuel Saving Technology

Due to the rising cost of fuel and other curing inputs, methods and technologies to increase curing efficiency have been investigated. Most recently, the use of variable firing rate burners that can better match the change in the thermal load during the curing process, thus potentially reducing the amount of fuel needed have been evaluated. A more mature technology used widely in industry to improve fuel savings is the use of automatic ventilation and temperature controllers. Figure 1-3 shows an automated temperature controller mounted in the back of a barn. The controller continuously adjusts the fresh air damper to maintain the desired wet-bulb temperature throughout the curing process. Automatic temperature controls advance the dry-bulb temperature during the yellowing, leaf drying, and stem drying phases. The automatic temperature advance feature is very similar to existing barn controls, but simultaneously controls the damper. Automatic temperature controllers demonstrated as much as a 15% savings of the total fuel usage compared to manual control of the curing environment (Ellington, 2006). However, the fuel savings are reduced if a grower is manually using a wet-bulb thermometer to control the ventilation; automatic controllers do aid all growers by making ventilation adjustments without the grower being present. The time management benefits of these controllers are appreciable but are more difficult to quantify than any fuel savings.

Tobacco farms continue to increase in size since the federal buyout and as a result many farmers have 50 to 75 barns in a central location. An additional management tool available with automatic temperature controllers, if desired, is the ability to remotely monitor the curing conditions in all the barns. This minimizes the time typically spent by a grower checking the barn conditions throughout the curing season. Additionally, these systems are equipped with alarms to notify the grower when the curing conditions are not as desired or when other malfunctions are detected, which allows growers to respond to any problems and prevent damage to the tobacco. Figure 1-4 is a photo of a remote monitoring system for automated temperature controllers.

1.2 Electricity Saving Technology

Variable frequency drives (VFDs) are commercially available to use on existing fan motors in order to decrease the fan speed as moisture is removed and the resistance to air flow decreases. Ideally, the volume flow rate of air provided would be constant throughout the cure. VFDs are common in industrial applications such as controlling assembly lines or large air circulators. Until recently, VFDs rated to interface with a tobacco barn fan motor were not available or, if available, were cost prohibitive. Farms in general and tobacco farms specifically, are major consumers of electricity in rural areas during the curing season months of July through October. The curing season also corresponds with the hottest months of the year in the tobacco producing states when residential demand for electricity is elevated. Peak demands can tax the rural power distribution facilities causing service interruptions and rate increases. With the recent push towards sustainable energy and the reduction of consumption, many electricity providers are offering incentives such as cost share programs to implement energy saving devices. VFDs qualify for these programs as well as USDA energy grants, making them very attractive economically to tobacco producers (Tucker, 2009). VFDs are implemented between the power feeding the fan and the fan motor. They function with either single-phase or three-phase input power and vary the frequency to slow the speed of the fan. The unit is physically similar in size to the automatic temperature controllers used on barns today. There has been very little work on the application of VFD technology in tobacco curing. In order to efficiently utilize this technology, research reported in this thesis was undertaken to assist with optimizing at what point during the curing process and the lower limit to which the fan speed should be reduced for energy savings.

There are numerous types of barns with various heat exchangers in use today. Barn variations include size and number of boxes, racks, presence of floors in the barn, plenum height, fan configuration, and fan orientation in relation to the heat exchanger. Additionally, the amount of tobacco placed in the curing boxes (packing density) changes through the harvest season. These variables can also affect airflow through the barn and the tobacco. Tobacco quality changes seasonally depending on the variety, cultural practices and the growing environment.

For these reasons, continuous evaluation of any schedule for reducing the fan speed is needed to determine any necessary changes in the reduction.

1.3 Research Objectives

The major goal of this research was to collect preliminary data using commercially available VFDs to reduce the fan electric motor speed in flue cured tobacco barns in order to reduce electricity consumption. Five primary goals were established with the implementation of VFDs:

- The act of reducing the fan speed should not detrimentally affect quality. If there is a noticeable change in the quality, the technology will not be accepted by the growers regardless of the electrical savings.
- Reducing the fan speed should not increase curing time. Growers are producing more tobacco with fewer barns in the modern production systems, making curing time critical. Reducing fan speed should not increase the time it takes to complete the curing cycle.
- Heat exchanger temperatures should not increase greatly by reducing the fan speed. Reducing the amount of air that moves across the heat exchanger may cause the surface temperature to rise, possibly damaging or reducing the life of the heat exchanger, or reducing the efficiency of the heat exchanger. Temperatures should be monitored to determine how much, if any the temperature increases with reduced fan speed.

- The VFD should reduce the total amount of electricity required for the cure. Appreciable electrical savings must be obtained to make this technology economically feasible.
- A by-pass switch should be integrated into the system to allow for normal line power to be re-energized in the event of a VFD failure. The application of this technology is new and should some unforeseen problem occur, the grower needs to have a backup plan in place to be able to restore air flow to the barn.

Each of these goals should be implemented in the most efficient way at each individual site depending on the variables present at that particular location.

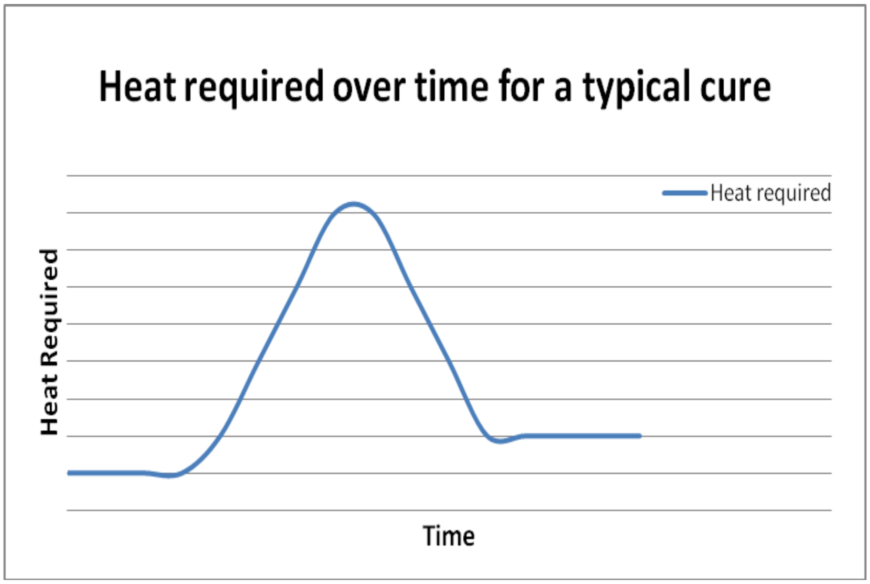

Figure 1-1: Typical heat requirement for a cure

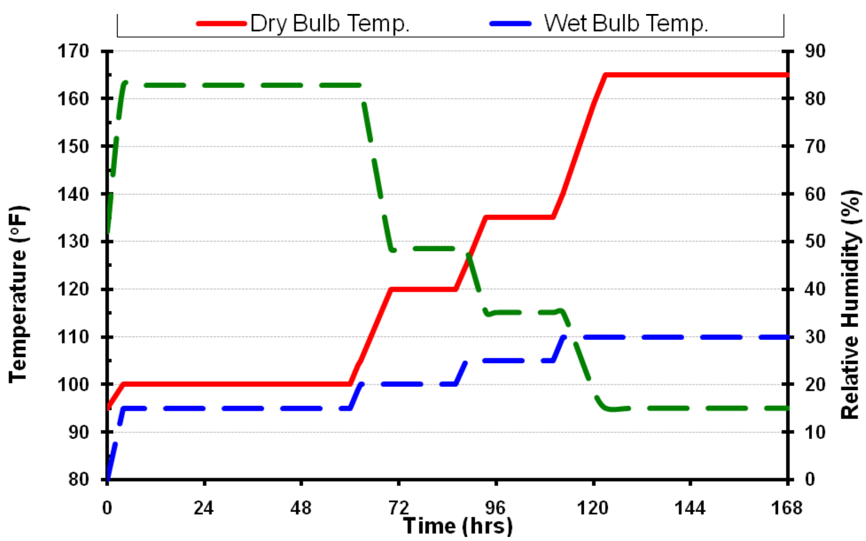

Figure 1-2: Typical curing schedule for a cure

Figure 1-3: Automated curing controller mounted in a tobacco barn

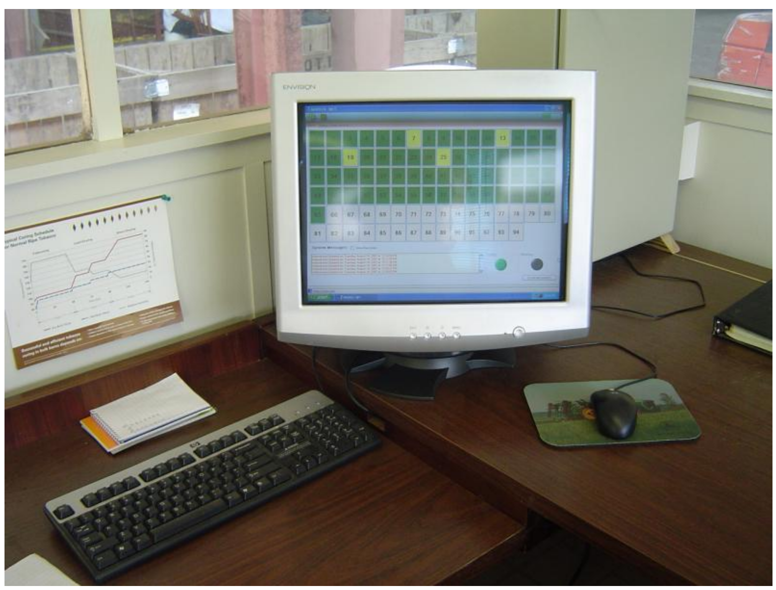

Figure 1-4: Remote monitoring system for automated curing controllers

2. LITERATURE REVIEW

The literature related to this research divides naturally into three areas of interest: air flow, heat addition, and control systems. By looking at the research done in all three areas, a starting point for combining the VFD fan control and the existing controls in their many variations may be determined. The utilization of control systems to control these processes simultaneously has been investigated based on previous developments of similar control systems for tobacco curing as well as other agricultural processes. This research is focused on the implementation of the VFDs on existing fan motors with the possibility of automatic control technology in the future.

2.1 Air Flow

Air flow has been investigated with different types of tobacco particles (i.e. chopped-leaf, whole leaf) and containers in several different studies. For example, the pressure drop across two different style curing containers and various orientations of the leaf arrangement in these containers has been studied (Suggs et al., 1985). The air flow decreased as the density of the tobacco increased as did the slope of the pressure drop versus air flow on a log-log scale (Suggs et al., 1985). In addition, the slope values obtained for tobacco were similar to other crops although the tobacco slopes were in the upper end of the range of values. Several different styles of curing containers have been developed since the Suggs study, most of which are larger than those used in the study. A more recent study by Anderson, et al., from 1998 continued this research for larger containers and found that the relationship of pressure drop per unit depth of tobacco was nearly linear on a log-log scale. The research evaluated the use of three equations for estimating the pressure drop through packed green tobacco and defined experimental constants for each of the equations (Anderson et al., 1998). Air flow recommendations of 0.5 cubic feet per minute (cfm) per pound of fresh green tobacco are still applicable for optimum curing (Suggs et al., 1985). A potential control algorithm could be to maintain the 0.5 cfm per pound of tobacco utilizing a VFD on the fan motor because the weight of the tobacco decreases with moisture removal. Later studies of chopped-leaf particles indicated that using similar methods, chopped particles followed similar linear log-log relationships to the whole leaf particles and can be normalized to make possible reverse calculations of pressure drop using densities not actually measured (Suggs et al., 1986). One significant difference noted between tobacco leaves and other agricultural products such as grains, seeds, and potatoes, is that air flow measurements are normally only taken at one loading density. However, air flow measurements through tobacco must be taken at several densities due the fact that tobacco can be compressed into containers much more readily than grains or bulk materials without damaging the quality of the product (Suggs et al., 1986).

Electrical energy saving strategies associated with curing tobacco have been investigated in the past. Previous work investigated electrical savings from cycling the fan on-off for various duty cycles and how the process affects the quality of the cured leaf (Maw et al., 1985). Fan cycling was also accompanied by burner cycling to prevent the burner from firing during the time when the fan was not in operation. Thus, there is some potential for fuel savings in addition to the electricity savings.

Electricity is only 10 to 15% of the energy required to cure the tobacco but overall accounts for 20% of the cost of curing the tobacco over the duration of an entire season (Cundiff, 1978). This percentage is affected by the cost of the electricity, quality of the tobacco, and the size of the fan motors. Tests of fan cycling with the fan operating for 22.5 minutes and then off 7.5 minutes for each 30 minute period during a six hour period of each day resulted in electricity savings of approximately 0.023 kilowatt-hours (kWh) per pound of tobacco (Maw et al., 1985). This demonstrated that reducing the time that the fan operates by one fourth, the amount of electricity consumed per weight of cured tobacco was decreased by approximately 11% as compared to the fan operating continuously. In addition, no significant increase in the curing time or any decrease in the cured leaf quality was observed cycling the fan versus the fan operating continuously (Maw et al., 1985). If not operating the fan for some period of time does not damage the quality of tobacco then reducing the fan speed and air flow with VFD technology at some point in the cure and continuing to decrease the fan speed as the resistance decreases may provide even more electricity savings while still maintaining the desired cured leaf quality.

The use of VFD technology in industry has demonstrated significant energy saving potential. In greenhouses where fans are used for primary ventilation to control temperature, VFDs have demonstrated energy savings approximately 36% less than fans that cycle on-off (Teitel et al., 2004). The fan in a greenhouse typically starts when the temperature exceeds the desired value; ventilation of the structure is required until the temperature is back within the defined range. In the above cited research, the VFD controlled fan was operated with a controller determining the fan speed based on the temperature in the greenhouse and incoming radiation. The speed ranged from 0 to 100% of normal fan speed, depending on the time of day and the ambient temperature. It was found that in cooler ambient conditions, the on-off fan provided large temperature spikes from the time that it came on to cool the house until it shut off while the fan with the VFD provided a much more uniform temperature inside the greenhouse due to the continuous fan speed adjustment (Teitel et al., 2004). Similarly, a tobacco curing structure utilizing the same type of fan control can potentially save significant amounts of electricity and maintain the desired temperature in the barn.

A pilot study of VFD use on tobacco barns was conducted during the 2008 curing season. A VFD was installed on one barn in Lenoir County, NC and operated during four cures at the end of the curing season. This research resulted in an average savings of approximately 12.68 percent electrical energy over three of the four cures (Ellington, 2008). The first cure of the pilot study resulted is some deterioration in quality and was not considered in the average savings. However, no detailed records of when the fan speed was reduced or how much the fan speed was reduced were available. The study did result in electrical savings but also resulted in one cure in which the tobacco was damaged. Information from the pilot study was used in the development of the current research.

2.2 Barn Heating

The burner efficiency in tobacco curing barns is an area related to fuel savings where the least research has been done. There has been work done on cost savings using different types of fuel other than either liquid propane or natural gas as well as the use of hot water boilers to supply the heat. One study was conducted comparing an electric heat pump curing system to a conventional liquid propane barn. This system used heat pump dehumidification to remove the moisture from the barn at relatively low fan speeds (Maw et al. 2003). However, the cost of curing with the electric heat pump was found to be roughly twice that of the conventional barn based on a cost per cured weight relationship (Maw et al., 2003). Since most farmers use traditional gas or oil fired burners, the conversion from the traditional burner to a variable firing rate burner would be a less complex issue, making it more acceptable to the industry. A variable firing rate burner would allow the heat supplied to vary with demand throughout the curing process rather than having a fixed output as burners currently in use do. This would be more efficient and use less gas than the cycling of a high firing rate burner. Though not yet commercially available, variable firing rate burners are being researched in other projects.

Another source of potential cost savings relates to alternative fuels. It has been demonstrated that using wood as a fuel source to heat water for curing tobacco reduced curing costs by approximately 1/8 to 1/4 that of curing with liquid propane gas (Boyette et al., 1986; Macialek, 2009). Although this is a significant reduction, the system requires a large capital investment as well as the possibility of more intense management although fully automatic systems will soon be available. Hot water systems also require a radiator to be installed in each barn, thus increasing startup costs. The goal of this research is to develop a system compatible with existing systems to minimize the capital costs of retrofits required for equipment and curing barns.

In the study discussed earlier on fan cycling, it was also determined that the fan cycling barn saved approximately 0.0156 gallons of fuel oil per pound of cured leaf over the conventional barn, amounting to a total of approximately 270 gallons for the season of 7 cures (Maw et al., 1985). This is an additional benefit associated with reducing the fan speed, but the recent increase in fuel prices during the curing season could overshadow the electrical savings. With the present economic trends, fuel prices are increasing significantly along with other petroleum based inputs such as fertilizers. With profit margins decreasing, saving a few gallons of fuel per cure could make a significant difference on the viability of producing flue-cured tobacco.

Because the direct-fired burners produced compounds that resulted in tobacco specific nitrosamines (TSNA's) in the cured leaf, (known carcinogens), tobacco growers were compelled in the late 1990s to retrofit all of their barns with an indirect-fired burner. These systems utilize heat exchangers that are heated by gas burners. Adding a large heat exchanger into the air stream increases the air resistance which, in turn, increases the surface temperature of the heat exchanger. With a variable firing rate burner, the heat input could be decreased during decreased fan speed operation to allow for lower heat exchanger temperatures, thus reducing thermal stresses and increasing the effective life of the heat exchangers. There is potential for shortening the cure due to the fact that ceasing fan and burner operations during fan cycling studies in the past did not increase the curing time; being able to run the fan and burner continuously at a reduced speed should not increase the curing time and potentially could actually shorten it due to the continuous operation albeit at a reduced capacity.

2.3 Control Systems

Many types of automatic controllers are currently available. These controllers primarily control the ventilation based on the relative humidity inside the barn indirectly measured by a wet-bulb thermometer. These controllers reduce the common problem of over-ventilation and have often been shown to significantly reduce fuel consumption (Ellington, 2008). These control systems also minimize the time associated with managing the curing process. The controller monitors the curing conditions and automatically makes adjustments to the fresh air dampers and modulates the burner firing frequency to maintain the prescribed conditions.

Control systems utilize a prescribed curing schedule, based on either farmer experience or developed schedules, for desired temperature and relative humidity (Abrams et al., 1990; Carroll, 2000). These control systems also provide the capability to remotely monitor and provide adjustments via networks and telecommunications for better curing management, especially for growers with large scale operations (Abrams et al., 1990). These systems are relatively inexpensive, with a modern system costing approximately $1400 per barn. This includes everything needed to control the burner and ventilation as well as the temperature sensors for monitoring the wet-bulb and dry-bulb temperatures in the barn. Continuously monitoring and adjusting the ventilation results in more consistent temperatures and relative humidity control throughout the curing process. Additionally, improved temperature control potentially results in reduced fuel consumption. A study of curing houses in Cuba demonstrated a fuel savings of approximately 47% by automatic control of humidity and temperature (Alvarez-Lopez et al., 2004). As ambient temperatures decrease near the end of the curing season, the fuel saving potential associated with minimizing over-ventilation increases.

Other control systems in agricultural postharvest processes have effectively used automated controls to dry grain. One system monitors moisture inside a grain bin filled with high moisture corn as well as the ambient conditions to determine the best time to operate the fan most efficiently and to prevent over-drying the corn (Bartosik et al., 2006). This system also controls supplemental heat during high humidity ambient conditions to remove moisture from the stored grain using a self-modulating variable fan and burner control versus the traditional ambient air inflow control (Bartosik et al., 2006). This system adjusts itself to provide only the airflow and heat desired.

Tobacco in bulk containers is not loaded uniformly due to random box loading patterns and irregularly shaped leaves, thus providing for irregular air flow and often inconsistent heat transfer. This makes the process of monitoring the moisture inside the curing container much more difficult. Current control systems monitor the condition of the free air inside the barn but outside the curing containers to control the air flow and burner firing based on the wet-bulb temperature and dry-bulb temperature, respectively. One problem associated with wet-bulb thermometers is that the wicks dry out near the end of the cure when the most heat is being added to the barn (Abrams et al., 1990). If the wick dries out, a false or inaccurate wet-bulb temperature results in over-ventilation and excessive fuel consumption (Abrams et al., 1990). Research is in progress utilizing an electronic relative humidity sensor to control the ventilation which eliminates the problems associated with wet-bulb thermometers.

A problem with using relative humidity instead of wet-bulb temperature is that the farmers are accustomed to using wet-bulb thermometers and are familiar with the corresponding temperature profile at various stages of the cure. A controller utilizing a relative humidity sensor is programmed to use this measurement, an algorithm based on pschyrometrics and the dry-bulb temperature to display the wet-bulb temperature. A relative humidity sensor will increase the curing management benefits by removing the maintenance of wet-bulb thermometers.

The use of variable rate burners and VFD fans requires advanced control algorithms. A variable firing rate burner would need adjustment at different stages in the curing process so that the appropriate barn temperature is maintained. It would be impractical for the burner to be on the lowest setting when the most heat was needed. Likewise, monitoring the static pressure drop, or air flow, is needed to know when and how much to decrease the fan speed. Under-ventilation causes scalding of the tobacco, a browning of the leaf as a result of increased temperature before an adequate amount of moisture is removed, causing serious deterioration in the quality of the cured leaf (Collins, 1993). The control system would need lower limit settings that could be changed with time or by operator adjustment to insure that neither heat nor fan speed falls below the minimum required for a quality cure.

3. Design

There were many variables to consider prior to the beginning of this research. The test locations were selected based on the growers' willingness to participate in the research being conducted, and the type of barns and heat exchangers that each grower utilized. Due to the wide variety of curing barns in use, different barn and heat exchanger combinations were selected to obtain the most information possible. Growers were also selected based on whether they were using single-phase or three-phase power. The management of the VFD controls and the collection of the data at the beginning and end of each cure were critical aspects of this research. Two barns of the same make and with the same heat exchangers were utilized at each site, one barn with the VFD controller and one barn to serve as a check, or control barn.

Fuel meter readings, electrical meter readings, the weight of green leaf loaded (where available) and weight of cured leaf from each barn were recorded for both the VFD and the check barn at each site throughout the season. Growers also recorded when during the curing cycle they reduced the fan speed and how much the fan speed was reduced for each cure. Locations were chosen in Johnston, Wilson, Edgecombe, and Person counties in North Carolina. The VFDs were assembled and installed by Custom Controls Unlimited (CCU), (Raleigh, NC, USA). CCU has a history working with agricultural operations and farmers on electrical control related projects. Also, CCU could provide support during the growing season should a technical problem arise during the middle of a cure, which is typical with this type of research.

3.1 Location Descriptions

The four locations chosen were in Johnston, Person, Wilson, and Edgecombe counties. Locations were very representative of the wide range of tobacco farms in North Carolina. All of the farms were family owned operations ranging from approximately 100 to 1000 acres of tobacco production, and each were also involved in several different commodities. A brief description of each farm's tobacco operation and infrastructure is provided below as background to the design of the experiment and implementation of the equipment.

3.1.1 Johnston County

The Johnston County location barns were 10 box capacity made by Long Manufacturing (Tarboro, NC, USA). The barns were in good working condition and retrofitted with Long Manufacturing heat exchangers. The barns were fueled by liquid propane (LP) gas and were powered by three-phase 10 horsepower electric fan motors and 36-inch diameter tube-axial fans. The tobacco was harvested using mechanical harvesters and the boxes were loaded using a Granville Equipment Precision Leaf Loader, manufactured by Granville Equipment Company of Oxford, NC. The curing process was controlled manually at this location. Two to three barns were typically filled per day throughout the season. The tobacco was baled on the farm and the cured leaf weights recorded.

3.1.2 Person County

The Person County location utilized 128-rack capacity barns made by Powell Manufacturing (Bennettsville, SC, USA). The barns were retrofitted with Decloet (Tillsonburg, ON, Canada) style heat exchangers and supplied with single-phase power. A 5 horsepower fan motor powered a backward curved centrifugal fan and the barns were fueled by LP gas. The tobacco was hand harvested and placed into the racks in the barn. This loading method did not provide a means for easily obtaining the tobacco green weight and was not recorded for this location. Typically this operation loaded one to two barns daily and the curing control was done manually. The cured weight was obtained from scales located on the baling equipment.

3.1.3 Wilson County

The Wilson County location had barns manufactured by various companies but most were Long and DeCloet manufactured barns. The barns chosen for the test were Long Manufacturing 10-box capacity barns. These barns were retrofitted with Reddick manufactured (Williamston, NC, USA) heat exchangers and the fuel utilized was natural gas. These barns had 10 horsepower tube-axial fans operating on three-phase power. This operation uses two Granville Equipment Precision Leaf Loaders to load from 12 to 18 barns each day. Each box in the barn was loaded with the same weight of green leaf, resulting in approximately identical total weights for the VFD and the check barn. The tobacco was mechanically harvested and transported to the barn site to load the boxes. This operation utilized automated curing controls with remote monitoring to decrease the time required to manage the curing process of over 100 barns. The weights of the cured leaf were recorded by the grower from the on-farm baling operation.

3.1.4 Edgecombe County

The Edgecombe County location barns were made by Taylor Manufacturing (Elizabethtown, NC, USA). The two barns chosen for the test were equipped with Taylor heat exchangers and tube-axial fans with 10 horsepower single-phase motors. Both barns were 10-box capacity and were filled using a leaf loading system fabricated by the grower to ensure each box was loaded with the same quantity of green tobacco. Typically, two to five barns were filled per day. All of the tobacco was harvested using mechanical harvesters and transported to a central location for handling. On-farm baling was used to determine the cure leaf weight taken from each barn.

3.2 Variable Frequency Drive Controller

The VFDs chosen were commercially available drives manufactured by

Schneider Electric Company (Palatine, IL, USA). Two model drives were used. On the 10 horsepower fan motors, Altivar Model 61 drives rated for 20 horsepower were used. On the 5 horsepower location, an Altivar Model 61 drive rated for 10 horsepower was used. The drives are compatible with any type of motor. No adaptations are needed to make the motor work with the drive. The drives were assembled by CCU with components chosen based on their experience with this technology. Since VFDs have not been utilized in this application before, extra precaution was taken to insure that the drives were adequately protected. Each drive was enclosed in a weatherproof cabinet to protect it from the elements. The enclosure mounted on a barn is shown in Figure 3-1. The cabinets also were equipped with auxiliary cooling to minimize overheating during operation. CCU also included line reactors in each of the units. The purpose of a line reactor is to reduce current fluctuations in the supply power to the VFD to insure better operation by using coils of wire in the reactor that act as an inductor (Streicher, 2002). Therefore, an instantaneous spike or drop in line voltage will not affect the current as quickly. Large circuit breakers and by-pass switches were also included in the drive for ease of operation and installation in the barn. The inside of the enclosure is shown in Figure 3-2. The operation of the drive is the first part of the process. Utilizing the drive to accomplish energy savings is the other challenge. The maximum fan speed reduction attainable was unknown and could be limited by many factors, including the heat exchanger temperature, moisture loss, and length of cure. All of these parameters were monitored and are elaborated on in subsequent sections.

3.2.1 Power Savings

The operation of a VFD is a complicated process. VFDs are used on alternating current (AC) systems. The electrical supply is converted to direct current (DC) and passed through a series of rectifiers that smoothes the waveforms and creates a steady DC voltage (Polka, 2010). This DC signal can then be varied to manipulate the resulting frequency after it passes through the inverter to be converted back to AC power. The speed of electric motors is governed by the equation:

$$N = \frac{120 * f}{P} \tag{3.1}$$

where:

N motor speed, revolutions per minute (RPM)

f frequency of supply, cycles per second

P number of poles in the motor

The amount of energy that the motor consumes at an efficiency of 100% can be calculated using the formula:

$$P = hp * 0.745699872 * t \tag{3.2}$$

where:

P power consumed, kilowatt-hours (kWh)

hp horsepower of the electric motor

t amount of time the motor operates, hours

For a 10 horsepower motor operating continuously for 8 days, the minimum power consumption would be approximately 1432 kWh operating at 100% efficiency and full load. The actual power consumed will depend on the motor, the pitch of the fan blades, and the load on the fan. Fan laws are used to relate the motor speed and power consumed. The equation governing the power requirement for a given fan diameter and static pressure against which the fan operates is:

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3 \tag{3.3}$$

where:

P_1 power requirement prior to speed reduction, kilowatts (kW)

P_2 power requirement after speed reduction, kW

N_1 motor speed prior to speed reduction, rpm

N_2 motor speed after speed reduction, rpm

This relationship demonstrates that the power required varies with the ratio of the motor speed cubed. As a result, small reductions in the fan motor speed can result in large reductions in the power required. This performance characteristic was used to reduce the electricity consumption. Air flow also decreases with a decrease in fan speed which is why the speed reduction occurred near the end of the cure when resistance to flow was lower and the air volume required was less.

In addition, the VFD has a ramp up feature to eliminate motor startup peak demands, which allows the motor to start gradually and ramp up to full speed in a time set by the user. The centrifugal fans were belt driven and this feature also reduced belt slip during startup, effectively reducing belt wear.

3.2.2 Power Supply and Output

VFDs can utilize single-phase or three-phase power on the input side. VFDs are also rated based on the motor that they will operate. Until recently, VFDs small enough to run five to ten horsepower motors were too expensive to use on tobacco barns. One negative aspect of VFD drives is that regardless of the input phase, the output is always a three-phase signal, which requires that locations with single-phase power change their fan motors to three-phase motors. On farms that already use three-phase power, the VFD was wired in parallel with the normal supply line so that if the drive malfunctioned, line power could be reenergized through the use of a switch, which allowed the grower to operate the fan normally and by-pass the VFD. However, farms supplied with single-phase power had no means to by-pass the VFD control because the motor was changed to operate on three-phase power. At these locations, in the event of drive failure, the motor was changed back to a single-phase motor and the drive was manually by-passed by wiring in a motor starter.

3.2.3 Safety Features

In addition to reducing the fan speed, the VFD must perform several other safety functions normally handled by the fan operation circuit. If the fan is not running, the burner will not engage. This is accomplished electronically and through the use of a mechanical pressure switch. Both the circuit and the mechanical pressure switch must be energized and operational in order for the burner to ignite, which is a safety measure to shut down the burner in the event of a fan motor failure or power failure and prevent barn fires. The safety features had to be rerouted through the VFD control panel. A second safety feature integral to the barn is a high-limit switch used to stop the burner if the temperature in the barn exceeds an upper limit. The high limit switch is also connected through the fan circuit, which had to be rerouted through the VFD controls.

The VFD incorporated several safety features during operation as well. The VFD had both high and low voltage protection. If voltage fluctuations occurred on the supply line, the VFD would shut down, saving the fan motor from possible damage. The VFD also incorporated thermal overload protection. If the VFD or the motor temperature exceeded an upper limit, the VFD would shut off the fan motor. The VFD also had phase to phase short protection as well as phase to ground short protection. The enclosure containing the VFD was equipped with cooling fans that were controlled with a thermostat. If excessive heat was generated from the VFD or the ambient conditions, the cooling fans would operate until the temperature in the enclosure decreased below the set point of 100 degrees Fahrenheit (°F). For operator safety, the VFD control panel and switches were located on the outside of the enclosure, to reduce the exposure to the electrical connections and wiring. The external switches allowed all changes to be made easily without having to open the enclosure. The display and controls are shown in Figure 3-3.

3.3 Monitoring Energy Consumption

Energy monitoring equipment was installed on both the VFD and the check barn at each location. The same equipment was used on all the barns monitored. The energy consumption from both barns was recorded at least twice per cure, once at the beginning and once at the end. The grower chose when to record the data at the end of the cure when the tobacco was taken out, allowing for time spent ordering the tobacco to be counted as well as the normal cure time.

3.3.1 Monitoring Fuel Consumption

Barns selected were modern style barns in good working order without major defect. Liquid propane (LP) or natural gas was used to cure the tobacco at all the locations. Both barns at each location were outfitted with gas meters and electrical power meters in order to monitor energy consumption each cure. The gas meters used were manufactured by Elster American Meter (Nebraska City, NE, USA) model AL-425 diaphragm meters and purchased from Gardner-Marsh, Inc. (Raleigh, NC, USA). The fuel meter used is shown in Figure 3-4. Meters were installed by a gas service company and meter inlet pressure was set at 10 pounds per square inch gauge (psig). The meter records the standard cubic feet of gas used, but was converted to gallons using a conversion factor based on of the meter inlet pressure. For 10 psig, the conversion factor was 4.42. For natural gas, the meter reading is the number of therms, 100,000 British Thermal Units (Btu's), of natural gas which can be compared to gallons of LP. Only the Wilson county location utilized natural gas. Meter readings were recorded by growers at the beginning and end of each cure. Gas consumption was monitored in order to determine a baseline usage for each barn so that any changes in fuel consumption may be attributable to changes in the fan speed. Although fuel consumption is not directly related to fan speed, it is possible that less fresh air associated with a reduced fan speed may result in decreasing the burner on time, thus reducing fuel consumption.

3.3.2 Monitoring Electricity Consumption

On each barn, power meters were installed to record kilowatt-hour consumption during the cure. Meters were installed by an electrician from CCU at the same time the VFDs were installed in order to maintain consistency. Power meters were manufactured by Schneider Electric, model PM-210. The same meters were used on both single-phase and three-phase locations, with the only difference being the way that they were implemented. The single-phase locations required less current transformers and fewer voltage lines to be connected than the three-phase locations. The meters display amperage, voltage, and power for each leg as well as total power consumption. A meter in operation is shown in Figure 3-5. A current transformer (CT) was used to measure the amperage on each power leg supplying electricity to the fans. The three-phase locations required three CTs per barn while the single-phase locations required only one per barn. The meter was setup according to the instruction manual and which type of system, for example, single-phase, three-phase four-wire, three-phase three-wire etc., was being measured. Both meters at each location were set up the same way. Current and voltage readings were checked with a handheld digital multimeter to verify the meter values and determine if the installation was correct. Growers were shown how to reset the meters each cure, but were also given the option to keep a running total throughout the season if they were not comfortable with resetting the meters. The difference between the initial and final readings would be the electricity usage for that particular cure.

3.4 Temperature Monitoring

Temperature monitoring was another key aspect of the data acquisition portion of this design. The heat exchanger surface temperature in a barn under load was an unknown at the beginning of this research. The key concern with the heat exchanger temperature is in relation to the fan speed. When the fan speed is reduced, the airflow and air velocity will be less, possibly resulting in an increase in the heat exchanger temperature. Most of the heat exchangers in tobacco barns today are approaching ten years old if they have not already been replaced. A cracked heat exchanger allows undesirable combustion gases to mix with the airflow supplied by the fan and consequently, exposing the tobacco to these gases, which can have a negative impact on the cured leaf quality. An increased temperature will increase the effects of the thermal cycling already experienced by the heat exchangers and potentially reducing the life of the unit and accelerate potential for cracks.

A secondary concern was the effect the reduced fan speed would have on the transfer of heat and moisture removal from the tobacco. To evaluate this, one location was equipped with temperature sensors inside the barn to determine if there was any lag in how fast the heat moved through the tobacco. Growers at all locations were asked to pay special attention to their curing time and make note of any noticeable difference in time required to cure the barn equipped with the VFD versus the control barn.

3.4.1 Heat Exchanger Temperature

The temperature of the heat exchanger surface will vary spatially, but was estimated to be as high as 1200 °F. Temperatures this high cannot be measured by typical temperature sensors attached to the surface of the heat exchanger. The sensors would also be subjected to high humidity levels in the barn and excessive air speeds because of the heat exchanger's proximity to the fan. Additionally, the insulation on the wire needed to be sufficiently rated to resist the estimated heat exchanger temperatures. Also, the method of attaching the thermocouples to the heat exchanger surface must withstand the temperatures. The thermocouples were attached to the surface of each heat exchanger in order to accurately monitor the surface temperature. Both heat exchangers at each location were equipped with thermocouples to evaluate the effects, if any, reducing the fan speed had on the surface temperatures. Type K thermocouples, model GG-K-20 (Omega Engineering, Inc., Stamford, CT, USA) were chosen because of their temperature measurement range, -328 to 2282 °F, and their resolution, plus or minus 0.2 °F, in the operating range. The thermocouple wire was ordered in bulk and the thermocouples were made to length for each test location. The wire had fiberglass insulation rated to 900 °F. Thermocouple wire is made up of two wires consisting of different metals. The ends of the wire are soldered together and when heated, produce an electrical voltage that can be measured. This voltage is then converted to a temperature using a polynomial equation through the data acquisition software. The equation for type K thermocouples is an eleven part polynomial that is well established. The data logger stores the measured voltage and then, using the equation, outputs the temperature in either Celsius or Fahrenheit. The adhesive used to secure the thermocouple to the heat exchanger was OMEGABOND 400 high temperature air set cement (Omega Engineering, Inc., Stamford, CT, USA), with a maximum working temperature of 2600 °F. A small metal backing plate was used to increase the surface area of the wire to improve attaching the wire to the surface of the heat exchanger. In some cases, the cement did not hold because the heat exchanger surface was too smooth or the curvature of the surface was too great. In these cases, a magnetic type K , model MP1-K-36-SMPW-M thermocouple (Omega Engineering, Inc) was used to attach to the surface. The magnetic thermocouples performed well where there was adequate space to attach them and if the heat exchanger was constructed of a ferrous material so that a magnet could be attached.

Three thermocouples were used per barn. The first thermocouple was positioned on the heat exchanger surface on the same side the burner was located. The second thermocouple was placed on the side of the heat exchanger directly opposite the burner location. Figures 3-6 through 3-9 show various mounting positions of the thermocouples on the heat exchangers. The third thermocouple was placed in the exhaust stack to measure the exhaust temperature. Figure 3-10 shows a thermocouple mounted in an exhaust stack. Since the exhaust temperature is easier to measure than the heat exchanger surface temperature, this measurement could be used as an indicator of the heat exchanger temperature and of the heat exchanger temperature. A significant difference in heat exchanger exhaust temperatures between the two barns would indicate that one heat exchanger is reaching a higher temperature and should be monitored more closely. Because of the large number of different heat exchangers in use, this relationship will not always have the same ratio. Some heat exchangers transfer heat better than others and have lower exhaust temperatures. The exhaust stack probe was inserted through a 1/8-inch hole drilled in the side of the exhaust stack approximately six inches above where the exhaust exited the barn.

3.4.1.1 Thermocouple Data Logger

The thermocouple data were recorded with a model USB-5201 (MicroDAQ, Contoocook, NH, USA) eight channel data logger. The data logger is shown in Figure 3-11. The data logger stores the data on a compact flash memory card that can be removed and replaced. Data can also be retrieved by connecting to the data logger with a computer using the data logger software, Instacal, and a USB cable. The thermocouple measurements could be recorder for both barns at a given location on the same memory card for easier processing.

3.4.2 Barn Temperatures During the Cure

The temperature inside the barn was monitored using three temperature sensors and a model U12-006 HOBO (Onset Computer Corp., Pocasset, MA, USA) four channel external data logger. Figure 3-12 shows the HOBO data logger used. The temperature leads were TMC20-HD, also from Onset, enclosed temperature sensors that connected directly to the data loggers. Each barn at the Johnston

County location was implemented with this equipment. One temperature sensor was used to measure the wet-bulb temperature in the barn and the other two were dry-bulb measurements. The wet-bulb and dry-bulb temperatures are an indirect measurement of the relative humidity in the barn. The dry-bulb sensors were located both above and below the tobacco inside the barn and the wet-bulb sensor was located above the tobacco. These measurements were used to verify that there was no delay or lag in the temperature increase of the barn equipped with the VFD versus the normal barn. The fan must also provide enough air flow at the reduced speed to keep the wet-bulb temperature within the acceptable range.

3.4.3 VFD Enclosure Temperature

One concern in the operation and design of the VFD unit was the operating temperature of the drive itself. The enclosure's supplemental cooling capacity was sufficient but data was collected to determine if the back of the barn would be an acceptable environment for the drive and if the added expense of the enclosure is required primarily for cooling. In the pilot study, the drive was mounted directly in the back of the barn with no additional enclosure or cooling fans. The mounting location was changed for the expanded test due to concerns of drive stability during the curing process. To monitor these temperatures, a HOBO U10-003 (Onset Computer Corp., Pocasset, MA, USA) temperature and relative humidity data logger was placed in the VFD enclosure and at the back of the barn. These temperatures were monitored to determine the suitability of mounting the VFD directly in the back of the barn and eliminate the enclosure and associated expense. Measurements were collected at two of the test locations.

3.4.4 Temperature Logging Methods

No previous data for heat exchanger temperatures during the curing process were available. Based on the continuous burner cycling throughout the curing process, a fast sampling rate was utilized to measure the maximum temperature of the heat exchanger surface. The faster sampling rate was necessary to measure all of the peak temperatures throughout the cure. The sampling rate was set at 20 seconds for each of the three thermocouples connected to the barn. Two barns were logged on a single data logger for the duration of the cure. Because the data loggers utilized external data storage, the amount of memory available was not a concern. A tremendous amount of data points were generated during the 7 to 10 day curing cycle. The data were reduced from 20 second intervals to 10 minute averages using Microsoft Excel in order to reduce the total number of data points. The entire data file was used to determine the maximum temperatures because the averaging method reduced the overall magnitude of the temperature recordings. The reduced data was then used to plot the heat exchanger and the exhaust temperature profiles. The data loggers were programmed to begin logging five seconds after power-up in order to insure that any power interruption would not truncate the entire recording process.

The temperatures inside the barn during the curing process at the Johnston County location were sampled at a slower rate. The HOBO loggers sampling rate in the barns was set at two minutes. The HOBO loggers utilized internal memory for data storage. Also, the sampling rate was chosen to make sure that the logger could record the entire cure, even if more time than normal was required. The temperature inside the barn does not change as rapidly or as frequently as the temperature of the heat exchangers. The raw data were filtered to a 10 minute average to smooth out the data for plotting purposes.

3.5 Static Pressure Monitoring

Static pressure was monitored inside the test barns at three locations during the season. The maximum static pressure and the profile versus time throughout the curing cycle were recorded. The static pressure is a differential pressure measured across the tobacco inside the barn and is an indirect measurement of airflow. Most barns using large boxes have initial static pressure readings approximately 0.5 inches or less of water column. Static pressure is a maximum at the beginning of the cure and gradually decreases over time as the tobacco dries,
shrinks, and the resistance to airflow decreases. The static pressure decreases to an approximately constant value at or near the minimum usually late in the leaf-drying phase of the cure. Data were used to determine when the fan speed can be reduced. Monitoring the static pressure will also show any change in the curve when the fan

speed is reduced.

Static pressure was monitored using a model 2671005WD2DG2CN (Setra Systems, Inc., Boxborough, MA, USA) differential pressure transducer. Figure 3-13 shows the transducer mounted in a weather proof enclosure. The excitation voltage can vary from 12 to 40 volts DC and the output signal ranges from 0.05 to 5.05 volts DC corresponding to 0 to 5 inches of water column. A model S82K-00724 (Omron Electronics, Schaumburg, IL, USA) AC to DC power supply was also used. The power supply input was 120 volts AC and the output was 12 volts DC to the transducer. To record the pressure transducer output voltage, HOBO U12-012 (Onset Computer Corp., Pocasset, MA, USA) data loggers were used with a voltage input cable. The data logger range was only 0 to 2.5 volts which corresponded directly to 0 to 2.5 inches of water. However, this was not an issue because the maximum static pressures were always less than one inch of water.

The pressure transducers were installed at approximately mid-span of the barn length. Figure 3-14 is an illustration showing a section view of a loaded barn with arrows indicating the path of the air. The heat exchanger is not included in the illustration. Two 3/8-inch holes were drilled in the barn, one in the air plenum below the tobacco and one in the plenum above the tobacco. Tygon tubing was inserted through the holes approximately one inch inside the barn and the other tube ends were connected directly to the pressure transducer. The below the tobacco was connected to the transducer's high pressure inlet and the tubing coming from above the tobacco was connected to the transducer's low pressure inlet. The output voltage recorded was converted directly to static pressure in inches of water. Figure 3-15 shows the pressure sensor installed on a barn.

3.5.1 Static Pressure Logging Methods

The static pressure measurement was recorded every minute for each cure. The air flow in a tobacco barn is assumed to be turbulent flow because of the style and orientation of the fan. As a result, small fluctuations in the static pressure measurements were observed. Some of the pressure transducers measurement range was only 0 to 2.5 inches of water column, but the output was 0.05 to 5.05 volts. To get the actual static pressure reading from these units, the output voltage was divided by two. This differed from the transducers with a range of 0 to 5 inches of water column because the output voltage corresponded to the actual static pressure. The data for the static pressure was filtered to a 10 minute average similarly to the barn temperature data so that static pressure profile could be plotted on the same graph as the barn temperature data.

3.6 Experimental Methods

Maintaining the tobacco quality and not increasing the curing time were at the forefront of the experimental design. The fan reduction schedule should have no detrimental effect on the quality or length of cure. In addition, the temperature of the heat exchanger as well as the amount of electricity consumed would assist with determining the reduction in fan speed. Assuming the heat exchanger temperatures were not elevated and that electricity consumption is reduced, the decrease in fan speed and length of time operated at a reduced speed will increase until either quality or the length of the cure is negatively affected.

3.6.1 VFD Operation

Because the VFD was manually controlled, growers were instructed on how to operate the unit to reduce the fan speed during the cure. The VFD utilized a digital display with a rotary dial to vary the frequency to the fan motor. Table 3.1 shows the effect of fan speed reduction on power consumption. Growers were provided with a chart that showed the corresponding percent reduction in fan speed for various frequencies. For example, operating the fan speed at 95 percent of rated speed corresponded to a frequency of 57 hertz. The chart included values from 50 to 100 percent in 2 percent increments with 5 percent increments also included. The fan speed was reduced toward the end of the cure in the leaf-drying and stem-drying phases. At this point in the curing process, the tobacco had wilted and the resistance to air flow had dropped significantly compared to the beginning of the cure. The yellowing-phase is a critical time for adequate airflow. Inadequate airflow during this time can lead to many quality problems, including scalding and barn rot (Ellington, 2006). As a result, it was not recommended to reduce the fan speed during yellowing.

Another area to potentially save electricity was during the ordering process, or the humidification of the cured leaf inside the barn. The moisture content of the tobacco is essentially zero at the end of the cure. Moisture must be reintroduced to the tobacco so that it can be handled without shattering. The marketable moisture levels set by the buying companies ranges from 12% to 18% moisture in the cured leaf on a wet basis. The reduction schedules were continued through the ordering process, typically another 6 to 24 hours after the end of the cure. The fan continues to operate during the ordering process, but the burner does not.

Initially the barns were operated with the fan at normal speed to get a baseline on the energy use of the barn and the temperature of the heat exchanger surface. A conservative approach was taken in reducing the fan to insure that no tobacco or heat exchangers were damaged. After the first cure, growers were instructed to reduce the speed by 5 percent when 24 hours remained in the normal curing cycle. Usually with 24 hours remaining, the barn temperature is around 160 to 165 °F. Growers were asked to make note of any changes in the curing time or quality differences that might occur as a result of the reduced fan speed each cure. The next cure the fan speed reduction was adjusted to 5 percent reduction with 48 hours remaining in the cure. The barn temperature with 48 hours remaining is usually approximately 150 to 155 °F. After each cure, the electrical savings were reviewed. In addition, the heat exchanger surface temperatures were evaluated to determine if the heat exchangers were overheating as compared to the check at the beginning of the season. The fan speed reduction was changed to 5 percent at 48 hours total remaining and adjusted to 10 percent 24 hours later, or with 24 hours remaining in the cure. Based on discussions with the growers that reducing the fan speed was not having an adverse effect on the curing process and the heat exchanger temperatures measured, the schedule was increased once again. The next step was a 10 percent reduction in fan speed with 48 hours remaining in the cure. When no negative impacts on the curing time, quality or heat exchangers after this schedule modification, growers were encouraged to be as aggressive as they felt comfortable in the reduction of the fan speed. Once the growers were comfortable with the technology and procedure, the fan speed reduction and length of time operated at a reduced speed were increased. One location reduced the fan speed by 12 percent at a barn temperature of approximately 147 °F, which corresponds to approximately 54 hours remaining in the cure. Another location reduced the fan speed during the yellowing-phase of the cure at the beginning by 12 percent for the first 36 hours and again at the end of the cure by 12 percent for the last 48 hours. It should be noted that not all growers are able to decrease the fan speed during the yellowing due to the differences in fan size and output, quality of tobacco, and the amount of tobacco loaded in the barn.

Figure 3-1: Outside of the VFD control box

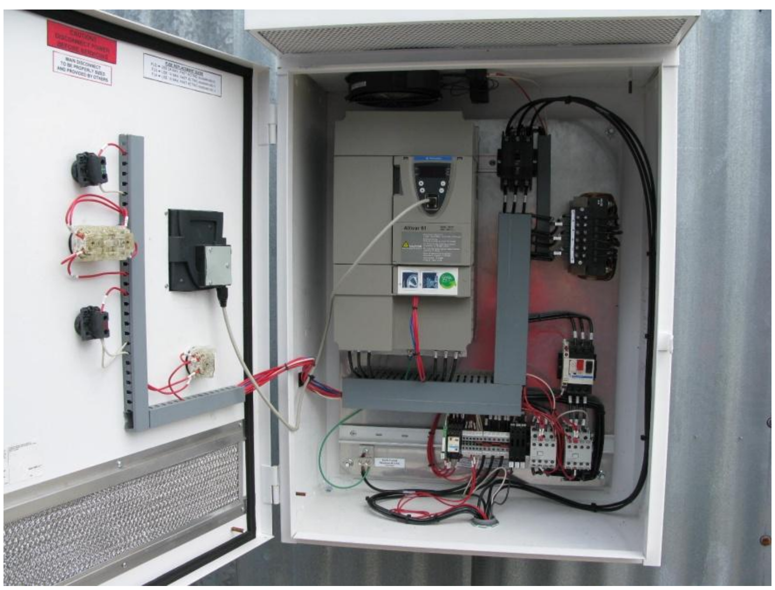

Figure 3-2: Inside of VFD control box, showing the VFD and Line Reactor

Figure 3-3: Close up of operator interface and frequency display on the VFD

Figure 3-4: Fuel consumption meter

Figure 3-5: Electricity consumption meter

Figure 3-6: Thermocouple mounted on Reddick Manufacturing heat exchanger

Figure 3-7: Close up of a thermocouple mounted on a Taylor heat exchanger

Figure 3-8: Thermocouple mounted on Taylor heat exchanger combustion chamber

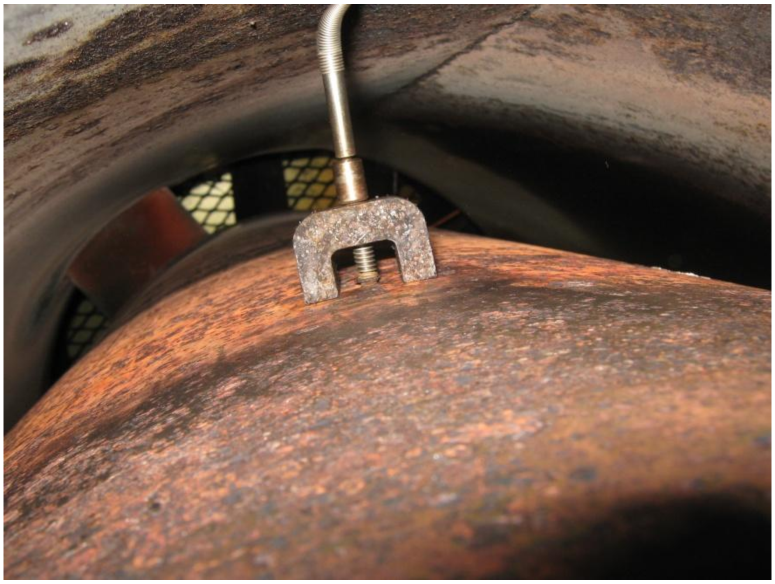

Figure 3-9: Magnetic thermocouple mounted on a Long heat exchanger

Figure 3-10: Thermocouple in mounted in an exhaust stack

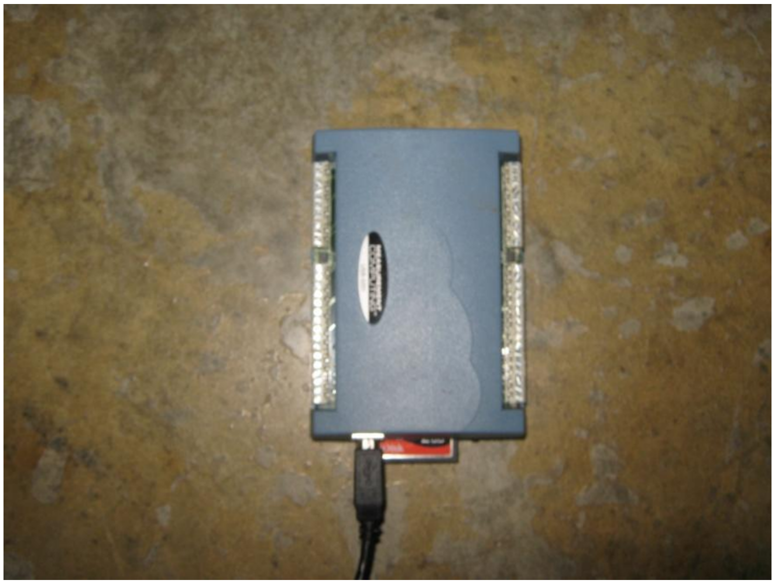

Figure 3-11: USB-5012 Thermocouple data logger

Figure 3-12: HOBO data loggers used to monitor barn temperature and static pressure

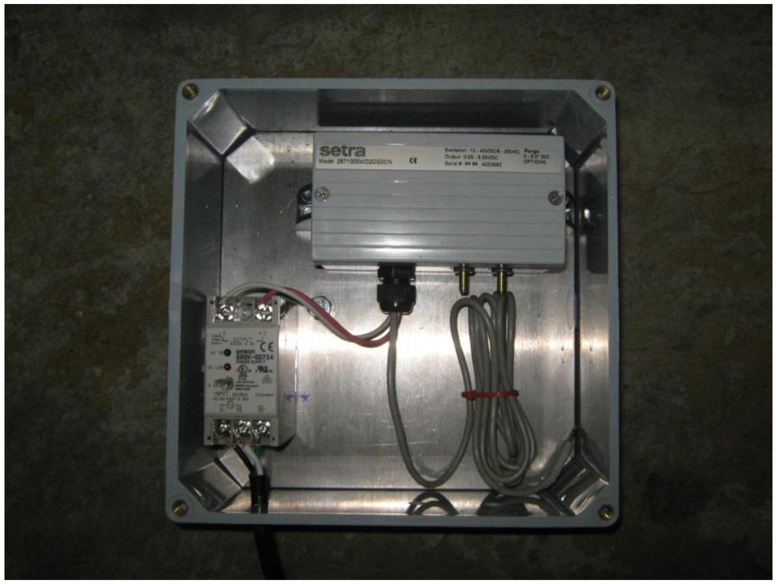

Figure 3-13: Static pressure transducer

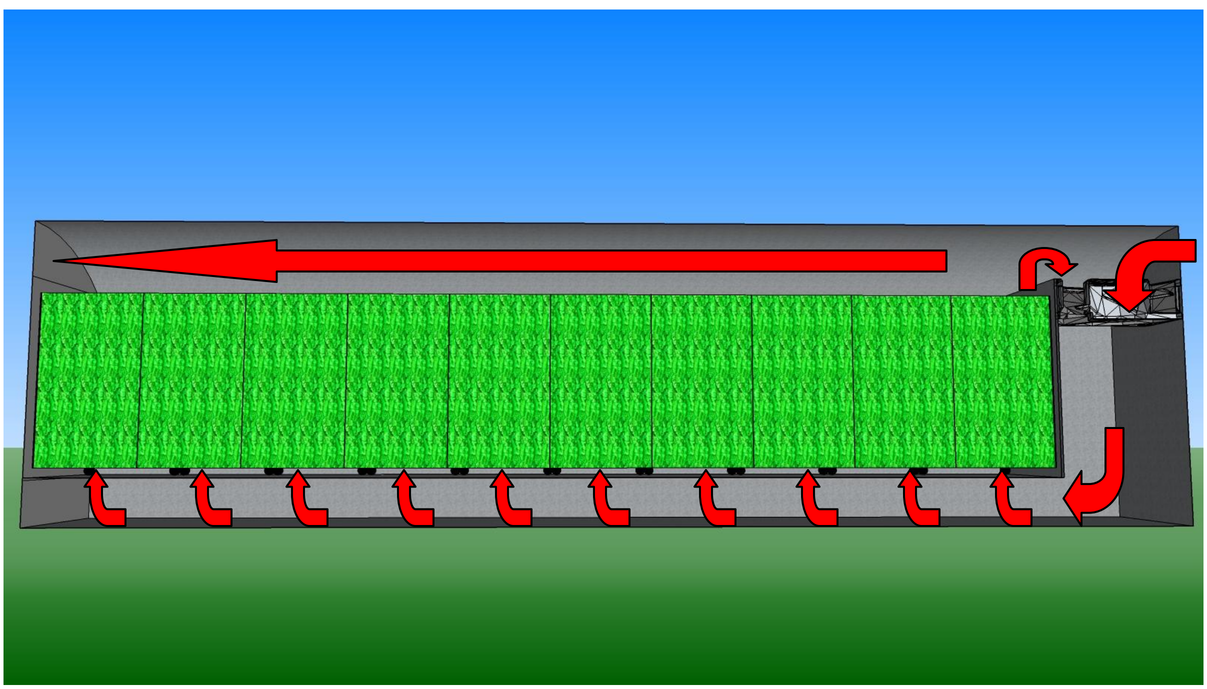

Figure 3-14: Barn Section Illustration

Figure 3-15: Static pressure monitor in place on a barn

Table 3-1: Effect of fan speed reduction on power consumption

Reduction in Fan Speed	**Reduction in Power Requirement**
5%	14%
10%	27%
15%	39%
20%	49%
25%	58%

4. Results

Data were analyzed after each cure to evaluate any differences in the heat exchanger temperatures and to quickly determine any electrical savings. A more in-depth analysis was conducted at the conclusion of the curing season. The analysis evaluated fuel consumption, electricity savings, and heat exchanger surface temperatures in the barn equipped with the VFD compared to the control barn. Additionally, the temperatures inside the VFD enclosure were compared to the ambient temperature in the back of the barn where the controls are typically located. A serial number was assigned to each cure. The data were then determined to be either useable or not useable and if not useable, for what reason. This serialization is shown in Appendix 7.1.

4.1 Fuel Consumption Results

The fuel consumption monitored during the curing season showed no difference in curing fuel usage between the VFD barn and the control barn as a result of decreasing the fan speed. The curing efficiency, or pounds of cured leaf per unit of curing fuel, did increase through the season. The quality and quantity of tobacco loaded per box typically increases as harvesting progresses up the stalk, resulting in better curing efficiencies. The curing efficiency at every location reached a maximum toward the latter half of the curing season. However, curing efficiency then decreased slightly at the end of the season due to the colder temperatures experienced in late September and October.

4.2 Electricity Consumption Results

The electricity consumption of each barn at each location was compared to determine any savings resulting from the operation of the VFD. The Johnston County location generated reliable data for each cure. The Wilson County location data for the VFD barn were reliable because the numbers were consistent and within reasonable expectations but the data obtained from the check barn power meter were questionable and inconsistent. The values obtained from the check barn were less than half of the expected values. Some of the energy consumptions for the check barn were lower than the barn equipped with the VFD due to equipment malfunction. The Person County data were incomplete due to the malfunction of the power meter during the first cure. The meter was replaced and usable data were generated the remainder of the season. The Edgecombe County location also generated reliable data for the entire curing season. The kilowatt-hour usage for each barn at each location was tabulated for analysis. Data are summarized in Table 4-1, and the savings at each location is summarized in Table 4-2. Table 4-2 excludes the first cure at each location because there were no reductions in fan speed. The Wilson County location had two cures at the beginning of the season and two additional cures halfway through the season with no reduction in fan speed. Therefore, only seven cures are displayed for Wilson County. The kilowatt-hour savings were also converted to a percentage of the amount of electricity the control barn used. All locations experienced positive savings from the VFD with exception of the Person County location. Savings at the Johnston County location ranged from approximately 107 to 251 kilowatt-hours, or approximately 6 to 16 percent savings. Wilson County savings ranged from approximately 133 to 240 kilowatt-hours, or on the order of 8 to 14 percent savings. The Edgecombe County savings were less, ranging from approximately 0 to 124 kilowatt-hours, or on the order of 0 to 6 percent. The Person County location showed mixed results. The VFD barn consumed approximately 9 and 42 kilowatt-hours more on two cures, but saved approximately 27 and 31 kilowatt-hours on two different cures. The increased usage was approximately 1.5 and 6 percent more than the check barn and the savings were both on the order of 4 percent on the two cures that experienced savings. Both the Johnston and Wilson County locations demonstrated an increase in electrical savings once the fan reduction rate was increased to approximately 10 and 12 percent during for the last 48 hours. Prior to increasing the fan reduction, the Johnston County location was averaging about 8 percent and the Wilson County location was averaging approximately 10 percent. When both the fan speed reduction and the length of time operated at the reduced speed were increased, the Johnston location averaged approximately 15 percent savings and the Wilson location averaged approximately 12 percent. The Edgecombe County location showed no trend over the season, averaging approximately 4 percent savings for the entire season.

The cured weight for each barn during the season allowed an electrical energy efficiency to be calculated by dividing cured leaf weight by kilowatt-hours used. The average efficiencies are dependent on the quality of the tobacco going in and the moisture content of the cured leaf coming out. Generally speaking, better quality tobacco weighs more and takes roughly the same amount of electrical energy to cure, thus increasing the electrical energy efficiency. Also, tobacco in higher order, or with a higher moisture content on a wet basis, weighs more than dryer tobacco, leading to increased electrical energy efficiency. Neither of these parameters were quantified so no comparison can be made. These data are included on the farm summary sheets in Appendix 7.2.

4.2.1 Statistical Analysis: Electricity

Statistical analysis was conducted on the electricity consumption from each location. A t-test comparing the means for paired samples was used to compare the season savings from the control barn and the VFD barn. Tests were conducted twice, once on the entire data set intact and once with the outliers removed from each data set. Only the test with the outliers removed is reported on although the full data results are included in Table 4-3. The difference was hypothesized to be zero for each test to determine if the differences were statistically significant. For the electricity consumption at the Johnston County location, the differences between the means of the control and the VFD barn were statistically significant ($p=0.00003$). The Wilson County location was analyzed and no significance was found ($p=0.433$).

This comparison has no meaning to the experiment because the data was incorrect. The results show the control barn having lower consumption than the barn with the VFD because of the faulty watt meter readings. The cause of this is unknown, but could be a wiring problem, a defective power meter or CT, a different fan motor or any combination of these. The cause of the lower readings was never determined. The Person County results were not statistically significant (p=0.224). The Edgecombe County location showed a significant difference (p=0.0059), even though the total savings were less than the other locations. These analyses are summarized in Table 4-3.

4.2.2 Unexpected Results

The Edgecombe and Person County locations did not demonstrate the electrical savings obtained at the Johnston and Wilson County locations. Person County had two VFD failures occur early in the season. The display on the VFD failed that resulted in disconnecting the supply power to the fan motor. This location used single-phase power and there was no system by-pass. The grower changed the fan motor back to the single-phase motor and was able to salvage the tobacco. When the display failed the second time, the grower reset the power and the display began functioning again. After this failure, the display was replaced and no further problems were experienced. It is unknown why the display failed.

At the Wilson County location, the power meter on the control barn read lower than expected the entire season. The meter electrical wiring was checked by the electrician that installed the unit and no problems were discovered. The meter was replaced halfway through the curing season with a new one, but the readings were still unexpectedly low. These readings were problematic when comparing the VFD electricity consumption to that of the control barn. To eliminate this problem, the power consumption was compared to the VFD barn cures when the fan was operated at full speed, or 1750 revolutions per minute. Cures were averaged and normalized for the number of days in each cure and then used as a comparison for each cure with a reduction in fan speed, which provided an estimate of the electrical savings in the absence of a direct comparison. The similarities between the Wilson and Johnston County locations, both being three-phase Long manufactured 10-box barns, gave an indication of what the values should be. This allowed for some comparison in the absence of data sufficient for a direct comparison.

At the Edgecombe County site, a power failure occurred affecting both barns. The circuit-breaker in the supply failed and as a result, supplied only 98 volts rather than the 240 volts required to both barns. The control barn fan motor was damaged but the VFD control measured the voltage drop and de-energized the motor in the barn, saving the motor and replacement cost. Another problem at the Edgecombe County site was associated with the fan blade configurations. When the motor was changed on the control barn, the fan blade was changed also. The new fan configuration had more blades, a different pitch, and was made from a different material. It is likely that the new motor and fan had different operating characteristics than the fan in the VFD barn. If the new fan configuration was delivering a higher volume of air or creating more static pressure, the loading characteristics on the motor would be different and the power consumption would no longer be comparable. The fan was changed for the last cure of the season so that both barns were using the same style.

4.3 Temperature Results

The heat exchanger temperatures were analyzed to obtain the maximum temperature on the heat exchanger and in the exhaust stack at each location. Data are summarized in Tables 4-4 through 4-7. The Long Manufacturing heat exchanger at the Johnston County location had the highest overall surface temperature of all the heat exchangers measured. This heat exchanger reached maximum temperatures of approximately 1090 °F on the side opposite of the burner during the season in the VFD barn compared to approximately 950 °F in the control barn. The maximum heat exchanger temperature for the season was approximately 870 °F for the VFD barn and approximately 840 °F in the control barn on the side of the heat exchanger closest to the burner. The exhaust temperature was approximately 400 °F in the VFD barn and approximately 340 °F in the control barn. The temperature difference between the control barn and the VFD barn gradually decreased through the system with the greatest differential being closest to the burner and the least difference occurring in the exhaust stack. The temperatures of the Reddick Manufacturing heat exchanger at the Wilson County location were lower. The maximum temperature of the VFD barn on the side opposite of the burner, the side with the burner and the exhaust locations were 440, 380, and 300 °F, respectively. The control barn temperatures peaked at 410, 430, and 300 °F on the side opposite of the burner, the side with the burner and the exhaust locations, respectively. The Person County location utilized a Decloet Manufacturing heat exchanger. The hottest temperatures obtained in the VFD barn were approximately 520, 530, and 180 °F on the side opposite of the burner, the side with the burner and the exhaust locations, respectively. The control barn temperatures were slightly higher with maximum temperatures of approximately 540, 590, and 200 °F on the side opposite of the burner, the side with the burner and the exhaust locations, respectively. Temperature data for cures 4 through 6 were not collected due to problems with the data logger. The Taylor Manufacturing heat exchanger maximum temperatures in the VFD barn at the Edgecombe County location were approximately 260, 690, and 230 °F on the side opposite of the burner, the side with the burner and the exhaust locations, respectively. The control barn temperatures were approximately 240, 780, and 200 °F on the side opposite of the burner, the side with the burner and the exhaust locations, respectively. It should be noted that the control barn heat exchanger was cracked near the burner side thermocouple location, possibly elevating the measured temperatures during operation. Some cures had readings two to four times as high as the maximum readings. These outliers were resultant of the thermocouple wire shorting out and giving false readings. These readings were included in the initial analysis but removed for the second test for significance and only the second test is reported.

4.3.1 Statistical Analysis: Temperature

All data sets contained some outliers and erroneous readings throughout the curing season. In order to obtain more meaningful results, outliers were removed for statistical analysis. The full data are shown in the tables and the Appendix but only the truncated data analysis is reported here. The Johnston County location temperature differences were significantly different on both the side opposite of the burner on the heat exchanger ($p=0.043$) and the exhaust ($p=0.048$). The Wilson County location temperatures were significant on both the burner side ($p=0.002$) and the side opposite the burner ($p=0.0002$) of the heat exchanger. The front temperature data was not a true indicator of significance because the thermocouple probe became partially detached early in the season and was not corrected. Therefore, the temperatures measured were closer to the air temperature than the actual heat exchanger surface temperature. The Person County location was significant on the burner side of the heat exchanger ($p=0.019$). Edgecombe County had a significant difference in the exhaust temperatures ($p=0.043$).

4.3.2 Barn Temperature Profile & Control Box Temperature Results

The barn temperature measurements were only recorded at the Johnston County location. The temperature profiles followed the expected profile for a typical curing schedule for flue-cured tobacco. The obvious stages of yellowing, leaf-drying, and stem-drying are clearly visible with no noticeable effect from the VFD operation. A representative plot of these data is shown in Figure 4-1. The data from the control barn and the VFD barn were very similar.

The enclosure temperatures at the Johnston and Edgecombe County locations were similar. The maximum temperature in the VFD enclosure at the Johnston County location was approximately 100 °F. The back of the barn was slightly hotter, reaching a maximum temperature of about 112 °F. The Edgecombe County location VFD enclosure maximum was approximately 120 °F while the maximum at the back of the barn was approximately 104 °F. The thermostat controlling the auxiliary cooling inside the VFD enclosure was set too high at the Edgecombe location and was adjusted to a lower value. After this adjustment, the enclosure reached a maximum temperature of 98 °F.

4.4 Static Pressure Results

The static pressure was recorded for the Johnston, Person, and Edgecombe County locations. The numbers were collected primarily for informational purposes rather than analysis. The tube-axial fans at the Johnston and Edgecombe County locations had similar static pressure profiles. Initially, they were at a maximum value and decrease approximately linearly over time until a steady state minimum was reached. The maximum values attained at the beginning of the cure were approximately 0.57 inches of water for the Johnston County location and approximately 0.70 inches of water for the Edgecombe County location. The minimum steady state values reached at the end of the cure were approximately 0.1 inches of water column for both locations. A representative graph of the tube-axial fan pressure relationship is shown in Figure 4-2. The centrifugal fan at the Person County location was different. The control barn maximum value was approximately 0.15 inches of water initially and the VFD barn was approximately 0.25 inches of water initially. These maximums are lower for this location because these barns are rack barns. The density and resistance to flow is much lower for racks than in a large box of green tobacco, thus reducing the static pressure required. The minimum steady state values were approximately 0.05 inches of water in the VFD barn and essentially zero inches of water in the control barn. Also, the static pressure profile was unexpected. Rather than a smooth linear decay, the pressure curve had an almost stepwise decay with the maximum pressure occurring more than once at several different points in the cure. This behavior is shown in Figure 4-3. The stair step nature of the profile is due to the adjustment of the fresh air damper by the grower. The static pressure generated by centrifugal fans is proportional to the resistance to air flow on the inlet side. Each peak occurs when the grower opened the fresh air damper one increment as the moisture was removed from the tobacco.

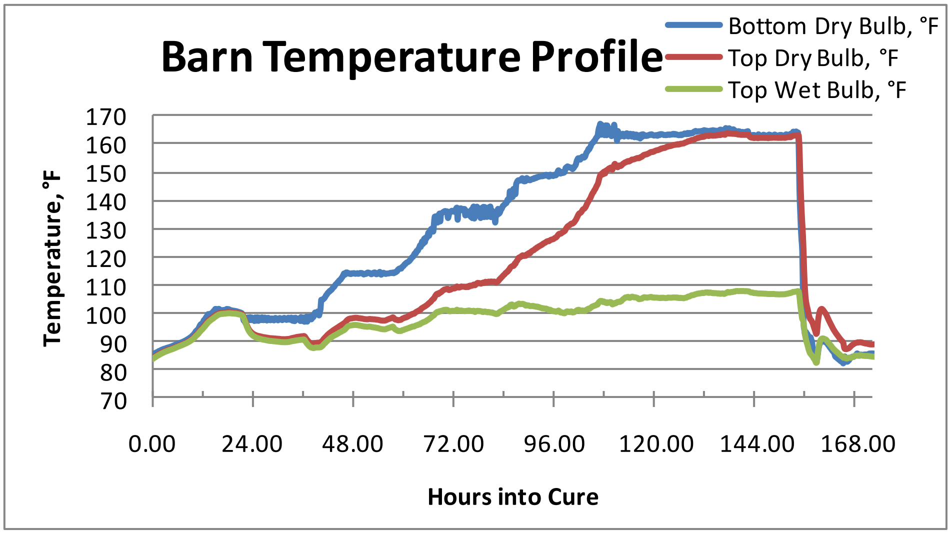

Figure 4-1: Temperature profile during cure JC-06-VFD

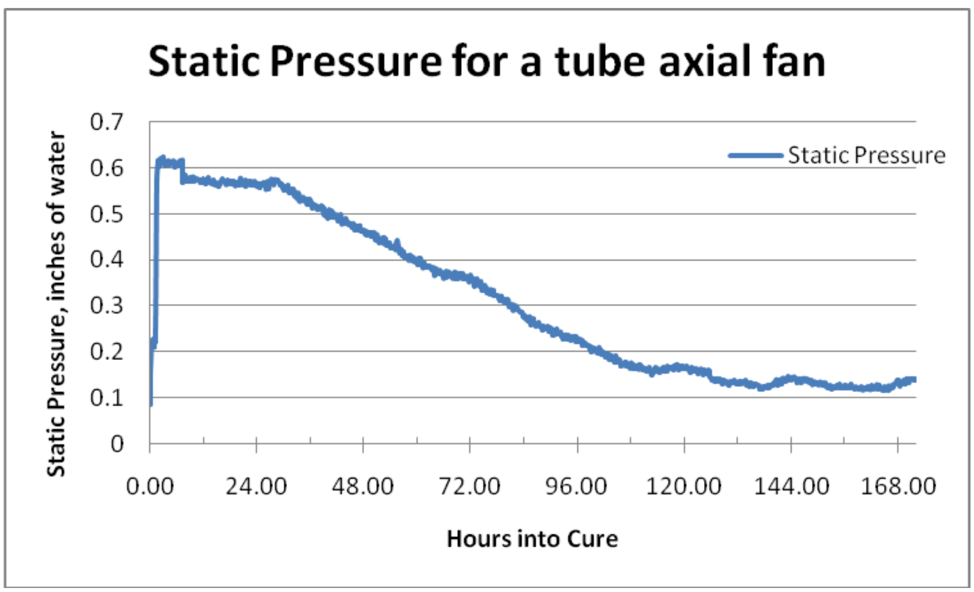

Figure 4-2: Static pressure curve for a tube-axial fan from cure JC-05-VFD

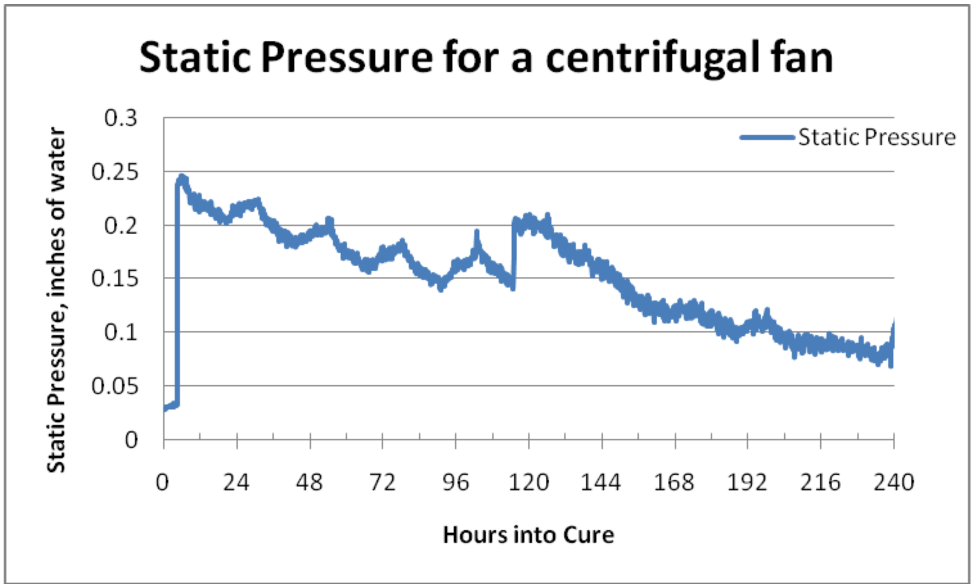

Figure 4-3: Static pressure curve for a centrifugal fan from cure PC-04-VFD

Table 4-1: Electricity consumption of two barns at four locations for the 2009 curing season

All numbers represent kWh

	Johnston County		Wilson County		Person County		Edgecombe County	
Cure	**Control**	**VFD**	**Control**	**VFD**	**Control**	**VFD**	**Control**	**VFD**
1	1587.086	1818.557	486.38	2205.49		643.895	1923.5	1846.9
2	1668.046	1551.9	842.48	906.81	512.58	647.109	1931	1897
3	1669.315	1562.2	1820.78	1867.1	605.38	614.45	1915	1802
4	1679.892	1522.4	1521.31	1512.96	657.8	700.05	1884	1881
5	1432.9	1307	1538.32	1562.5	676.7	649.7	2111	1987
6	1407	1202	1773.38	1884.9	682.6	651.2	1795	1686
7	1464.5	1250.2	326.17	1659.9				
8	1497.2	1256.8	549.05	1371.13				
9	1740.8	1489.6	1446.63	1435.52				
10			1931.45	1815.9				
11			1614.03	1531.43				

Table 4-2: Electricity savings of the VFD barn at four locations for the 2009 curing season

Johnston		Wilson		Edgecombe		Person	
kWh	**% Savings**	**kWh**	**% Savings**	**kWh**	**% Savings**	**kWh**	**% Savings**
116.146	7.0%	206.29	9.9%	34	1.8%	-9.07	-1.5%
107.115	6.4%	183.45	10.8%	113	5.9%	-42.25	-6.4%
157.492	9.4%	133.91	7.9%	3	0.2%	27	4.0%
125.9	8.8%	212.87	14.1%	124	5.9%	31.4	4.6%
205	14.6%	148.48	9.8%	109	6.1%		
214.3	14.6%	226.5	10.9%				
240.4	16.1%	240.97	14.2%				
251.2	14.4%						

Table 4-3: Statistical analysis results of electricity consumption: t-test for means of paired samples with alpha (α) equal to 0.05 and hypothesized difference equal to zero

	p values	
Location	Entire Data	Outliers Removed
Johnston	0.01357	0.00003
Wilson	0.04732	0.43333
Person	0.22418	0.22418
Edgecombe	0.00598	0.00598

Table 4-4: Temperature summary for Long Manufacturing heat exchanger

	Johnston County Long Heat Exchanger					
	Back Temp. (F)		Front Temp. (F)		Exhaust Temp. (F)	
Cure	Control	VFD	Control	VFD	Control	VFD
1	700.654	727	834.906	797.479	333.239	335.909
2	2157.33	172.586	823.141	842.402	337.237	343.018
3	985.964	1096.31	739.114	868.14	331.893	404.239
4	945.03	1094.38	178.746	835.885	330.342	344.337
5	760.49	734.295	110.26	453.993	223.001	679.239
6	DATA UNAVAILABLE		DATA UNAVAILABLE		DATA UNAVAILABLE	
7						
8	951.475	1062.09	775.801	609.516	326.486	342.961
9	571.676	1037.03	816.809	591.87	328.336	345.228

Table 4-5: Temperature summary for Reddick Manufacturing heat exchanger

	Wilson County Reddick Heat Exchanger					
	Back Temp. (F)		Front Temp. (F)		Exhaust Temp. (F)	
Cure	Control	VFD	Control	VFD	Control	VFD
1	3233.84	269.496	391.019	313.007	206.841	225.996
2	381.349	434.2	429.344	4411.33	283.259	296.808
3	380.746	420.388	185.235	327.61	283.174	287.75
4	391.882	393.313	187.512	312.364	288.518	264.887
5	383.325	438.909	184.739	366.096	288.883	294.959
6	381.923	401.431	190.101	335.147	285.687	277.326
7	408.309	405.018	201.926	343.131	294.386	280.276
8	387.408	426.025	189.645	374.284	287.535	293.763
9	362.868	430.915	177.144	379.327	269.069	291.094
10	382.317	418.042	203.45	366.952	280.015	282.126
11	394.872	396.78	178.999	354.8	282.839	273.103

Table 4-6: Temperature summary for Decloet Manufacturing heat exchanger

	Person County Decloet Heat Exchanger					
	Back Temp. (F)		Front Temp. (F)		Exhaust Temp. (F)	
Cure	Control	VFD	Control	VFD	Control	VFD
1	523.987	523.447	565.601	511.276	176.74	175.544
2	540.141	1045.69	591.719	531.068	195.456	148.24
3	516.89	518.388	549.589	520.223	162.782	4379.75

Table 4-7: Temperature summary for Taylor Manufacturing heat exchanger

	Edgecombe County					
	Back Temp. (F)		Front Temp. (F)		Exhaust Temp. (F)	
Cure	Control	VFD	Control	VFD	Control	VFD
1	176.904	190.664	451.384	2189.66	121.208	133.866
2	236.628	262.53	827.85	227.76	198.439	228.94
3	118.083	185.182	101.097	479.796	99.3151	131.364
4	DATA UNAVAILABLE		DATA UNAVAILABLE		DATA UNAVAILABLE	
5	234.456	230.445	775.952	688.676	177.36	183.917
6	245.877	237.024	779.555	680.716	205.74	202.215

Table 4-8: Statistical analysis results of temperature data: t-test for means of paired samples with alpha (α) equal to 0.05 and hypothesized difference equal to zero

	p values					
	Entire Data			Outliers Removed		
Location	Back	Front	Exhaust	Back	Front	Exhaust
Johnston	0.30730	0.20595	0.11586	0.04286	0.21394	0.04845
Wilson	0.19825	0.09693	0.35651	0.00176	0.00019	0.35651
Person	0.21078	0.01861	0.21466	0.36013	0.01861	0.24194
Edgecombe	0.11959	0.27075	0.04277	0.11959	0.13061	0.04277

5. Conclusions

The main purpose of this research was to develop a schedule for reducing the fan speed in flue-cured tobacco barns utilizing variable frequency drive technology to minimize electricity consumption while maintaining the cured leaf quality and not lengthening the curing time. The quality was not quantified but the growers provided feedback on the tobacco quality and if the length of the cure was different between the control and VFD barns. The barns equipped with VFD controllers did consume less electricity than the control barns at three of the four locations, but one location was not be statistically significant due to insufficient data. The Person County location resulted in electrical savings that were different and attributed to the different style fan. The total energy savings increased when the fan speed reduction was increased earlier in the curing process. The earlier in the curing process the fan speed was reduced and by the largest amount produced the greatest savings. The by-pass feature is a necessary component in the VFD control system to ensure the fan can operate when problems might occur with the VFD. Although the Person County location did not have a by-pass switch installed since it used single-phase power, the same type of failure could have happened anywhere.

Reducing the fan speed at each location was performed manually by the grower and as a result the management aspect affected the electrical savings of the tests. At the Edgecombe County location, the grower was not as meticulous as the other growers reducing the fan speed when scheduled. As a result, the data from this location did not demonstrate the electrical savings obtained at the Johnston and Wilson County locations. There were no fuel savings demonstrated with operating the fan at a reduced speed although it was originally thought this was possible. Although the fan output was decreased, the burner was still firing at the same rate, and consequently burning the same amount of fuel.

In some cases the heat exchangers in the barns with the VFDs were at significantly higher temperatures during operation, but if this difference is enough to produce a negative effect on the heat exchanger is unknown. Another variable that was unknown was the firing rate of the burners. The burner firing rate was not determined and there is no way to know if the rates were set the same. A higher firing rate could explain the temperature differences observed and when combined with the effects of the VFD could make the results significant.

Combining the static pressure and the barn temperature profiles for the same cure gave the most insight into when the fan speed could be reduced. The fan speed could be reduced when the static pressure reaches a minimum value near the end of the cure. The combined profiles are shown in Figure 5-1. There are two vertical lines on the graph. The solid line represents the point in the cure when the fan speed reduction actually occurred. The dashed line represents where the change in static pressure over time, or the slope of the profile, approximately reached a minimum and the fan speed reduction could have occurred. The space between these two lines represents the number of hours that additional electrical savings could have been obtained if the speed reduction was automatically programmed based on the static pressure. This time is equal to approximately half of the total actual time that the fan speed was reduced, representing the potential for a 50 percent increase in electrical energy savings.

5.1 Economic Impact

Having demonstrated that the VFD can reduce the amount of electricity consumed by a flue-cured tobacco barn, the next concern is the system cost and the payback time. Should the VFD package become commercially available and be mounted adjacent to the existing controls, the estimated cost range is $1,500 to $1,800 dollars per barn. The temperatures inside the back of the barn were not high enough during this test to restrict the drive unit from being mounted with the existing barn controls. A simple payback table was constructed using an energy savings of approximately 250 kilowatt-hours per cure based on the results of this year's test, the grower's electrical rate, and an assumed VFD cost of $1,500 dollars. The results are shown in Table 5-1. The electricity costs used in the table were varied from $0.08 to $0.15 cents per kilowatt-hour and the number of cures per barn per season ranged from 6 to 11. Most growers are using their barns 7 to 11 times per season and are paying between $0.10 and $0.13 cents per kilowatt-hour. Based on these assumptions, the payback time varied from approximately five years to eight years. Neither of these tables considered any cost share nor any applicable grant programs that are currently available, which would potentially decrease the payback time.

5.2 Future Work

The results from this research were promising for the barns with tube-axial fans. The centrifugal fan needs a completely different methodology to achieve similar savings. Due to the problems discussed at the location utilizing the centrifugal fan, an appropriate method to reduce the fan speed was not determined. It is possible that barns utilizing centrifugal fans will produce more savings if the speed is reduced earlier in the curing process when the resistance is higher due to the operating characteristics of the fan. Centrifugal fan power consumption increases as the fan load decreases. This is the opposite of tube-axial fans, which decrease power consumption as resistance decreases. Therefore, reducing the centrifugal fan speed early when the resistance is higher can effectively accomplish the same as closing off the fan intake with the fresh air damper. More work needs to be done to determine the appropriate time and amount to reduce the fan speed for centrifugal fans.

The locations with the tube-axial fans demonstrated that the technology can reduce the electrical consumption. However, automating the reduction in fan speed should be implemented to increase the process efficiency and maximize the potential of this technology. If the electrical energy savings was increased from 15 percent to

20 or 25 percent, the payback time will decrease to a range of 3 to 5 years. The modified payback table based on the increased savings is shown in Table 5-2. More work should be done automating the fan speed reduction. Static pressure or the dry-bulb temperature could be utilized as the input signal to control the reduction in fan speed. Future work should investigate how to implement these control parameters into an automatically controlled VFD system and continue evaluating the energy savings to assist with optimizing this technology application.

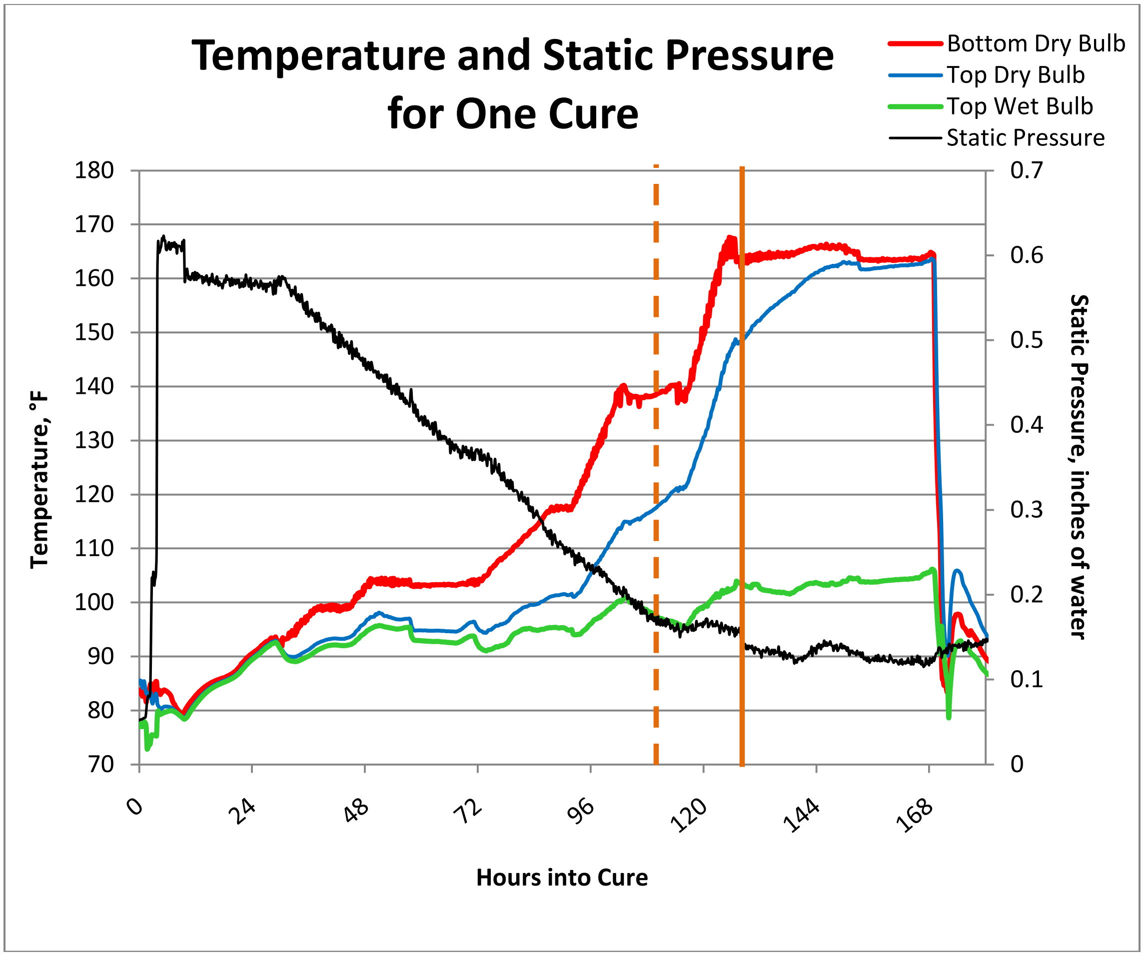

Figure 5-1: Temperature and static pressure data for cure JC-05-VFD. The solid vertical line represents where the fan speed was reduced. The dashed vertical line represents where the fan speed reduction could have occurred.

Table 5-1: Simple payback schedule for savings of 250 kilowatt-hours per cure from the study. The numbers in the table represent years to payback.

	Cost of Electricity							
# of Cures	**$ 0.08**	**$ 0.09**	**$ 0.10**	**$ 0.11**	**$ 0.12**	**$ 0.13**	**$ 0.14**	**$ 0.15**
6	12.5	11.1	10.0	9.1	8.3	7.7	7.1	6.7
7	10.7	9.5	8.6	7.8	7.1	6.6	6.1	5.7
8	9.4	8.3	7.5	6.8	6.3	5.8	5.4	5.0
9	8.3	7.4	6.7	6.1	5.6	5.1	4.8	4.4
10	7.5	6.7	6.0	5.5	5.0	4.6	4.3	4.0
11	6.8	6.1	5.5	5.0	4.5	4.2	3.9	3.6
12	6.3	5.6	5.0	4.5	4.2	3.8	3.6	3.3

Table 5-2: Simple payback schedule for savings of 375 kilowatt-hours per cure that may be possible with further work. The numbers in the table represent years to payback.

	Cost of Electricity							
# of Cures	**$ 0.08**	**$ 0.09**	**$ 0.10**	**$ 0.11**	**$ 0.12**	**$ 0.13**	**$ 0.14**	**$ 0.15**
6	8.3	7.4	6.7	6.1	5.6	5.1	4.8	4.4
7	7.1	6.3	5.7	5.2	4.8	4.4	4.1	3.8
8	6.3	5.6	5.0	4.5	4.2	3.8	3.6	3.3
9	5.6	4.9	4.4	4.0	3.7	3.4	3.2	3.0
10	5.0	4.4	4.0	3.6	3.3	3.1	2.9	2.7
11	4.5	4.0	3.6	3.3	3.0	2.8	2.6	2.4
12	4.2	3.7	3.3	3.0	2.8	2.6	2.4	2.2

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APPENDIX

7.1 Cure Serialization and Use Chart

Key:	Cure #:	Barn Description:
JC-Johnston County	Ex. 01, 02, 10 etc.	VFD-VFD Barn
WC-Wilson County		CHK-Check Barn
PC- Person County		
EC- Edgecombe County		

JC-01-VFD	Not used	PC-01-VFD	Not used, Equipment Malufnction
JC-01-CHK	Not used	PC-01-CHK	
JC-02-VFD		PC-02-VFD	
JC-02-CHK		PC-02-CHK	
JC-03-VFD		PC-03-VFD	
JC-03-CHK		PC-03-CHK	
JC-04-VFD		PC-04-VFD	
JC-04-CHK		PC-04-CHK	
JC-05-VFD		PC-05-VFD	
JC-05-CHK		PC-05-CHK	
JC-06-VFD		PC-06-VFD	
JC-06-CHK		PC-06-CHK	
JC-07-VFD		EC-01-VFD	

JC-07-CHK	
JC-08-VFD	
JC-08-CHK	
JC-09-VFD	
JC-09-CHK	
WC-01-VFD	
WC-01-CHK	Not used, Equipment Malufnction
WC-02-VFD	Not used, Equipment Malufnction
WC-02-CHK	Not used
WC-03-VFD	
WC-03-CHK	Not used, Equipment Malufnction
WC-04-VFD	
WC-04-CHK	Not used, Equipment Malufnction
WC-05-VFD	
WC-05-CHK	Not used, Equipment Malufnction
WC-06-VFD	Full Speed Cure
WC-06-CHK	Not used, Equipment Malufnction
WC-07-VFD	Full Speed Cure
WC-07-CHK	Not used, Equipment Malufnction
WC-08-VFD	

EC-01-CHK	
EC-02-VFD	
EC-02-CHK	
EC-03-VFD	Different fan configurations
EC-03-CHK	Different fan configurations
EC-04-VFD	Different fan configurations
EC-04-CHK	Different fan configurations
EC-05-VFD	Different fan configurations
EC-05-CHK	Different fan configurations
EC-06-VFD	
EC-06-CHK	

WC-08-CHK	Not used, Equipment Malufnction
WC-09-VFD	
WC-09-CHK	Not used, Equipment Malufnction
WC-10-VFD	
WC-10-CHK	Not used, Equipment Malufnction
WC-11-VFD	
WC-11-CHK	Not used, Equipment Malufnction

7.2 Location Summary Sheets

Johnston County Summary Sheets

	Barn 8 (Check)							Barn 9 (VFD)						
	Gas		Electricity		Dry Weight			Gas		Electricity		Dry Weight		
Cure	gal LP		kWh		lbs	lbs/gal	lbs/kWh	gal LP		kWh		lbs	lbs/gal	lbs/kWh
	0		0					1461		0				
1	85	375.7	1587.086	1587.086	3243	8.63	2.04	1558	428.74	1818.557	1818.557	3228	7.53	1.78
	85		0					1558		0				
2	171	380.12	1668.046	1668.046	3418	8.99	2.05	1651	411.06	1551.9	1551.9	3440	8.37	2.22
	171		0					1651		0				
3	258	384.54	1669.315	1669.315	3424	8.90	2.05	1743	406.64	1562.2	1562.2	3334	8.20	2.13
	258		0					1743		0				
4	339	358.02	1679.892	1679.892	3955	11.05	2.35	1829	380.12	1522.4	1522.4	4008	10.54	2.63
	339		0					1829		0				
5	424	375.7	1432.9	1432.9	3847	10.24	2.68	1922	411.06	1307	1307	4008	9.75	3.07
	424		0					1922		0				
6	517	411.06	1407	1407	3554	8.65	2.53	2025	455.26	1202	1202	3441	7.56	2.86
	517		0					2025		0				
7	623	468.52	1464.5	1464.5	4581	9.78	3.13	2137	495.04	1250.2	1250.2	4287	8.66	3.43
	623		0					2137		0				
8	719	424.32	1497.2	1497.2	4662	10.99	3.11	2244	472.94	1256.8	1256.8	4390	9.28	3.49
	719		0					2244		0				
9	822	455.26	1740.8	1740.8	4200	9.23	2.41	2356	495.04	1489.6	1489.6	4200	8.48	2.82
					Average	9.61	2.48					Average	8.71	2.71

SAVINGS						Fan Reduction Notes
	Gas	Electricity		Normalized Savings		
Cure	gal LP	kWh	% Elec.	lbs/gal LP	lbs/kWh	
1	-53.04	-231.471	-14.6%	-12.8%	-13.1%	
2	-30.94	116.146	7.0%	-6.9%	8.2%	
3	-22.1	107.115	6.4%	-7.9%	4.0%	Reduced 10% on 8/25 @ 20:00
4	-22.1	157.492	9.4%	-4.6%	11.8%	Reduced 10% 9/5 @ 8:00, 15% 9/7 @12:00, increased back to 12% @13:50
5	-35.36	125.9	8.8%	-4.8%	14.2%	Reduced 5% 9/14 20:00, reduced 10% @ 150° Top Temp. Off @ 13:40 9/17
6	-44.2	205	14.6%	-12.6%	13.3%	Reduced 5% 9/23 @ 151°T, 10% @ 153°T, 12% @ 158°T
7	-26.52	214.3	14.6%	-11.4%	9.6%	Reduced 8.33% 10/4 @161°T 19:50, 12% @ 21:00, Off 10/7
8	-48.62	240.4	16.1%	-15.5%	12.2%	Reduced 5% 10/13 @ 145°T, 12% @ 152°T, Off @22:00 10/17
9	-39.78	251.2	14.4%	-8.0%	16.9%	Reduced 5% @11:45 10/22 140°B/117°T, Back to 100% @14:55 152°B/122°T, Reduced 12% @8:05 10/23 166°B/143°T

Wilson County Summary Sheets

	Barn 58 (Check)								Barn 57 (VFD)							
	Gas			Electricity		Dry Weight			Gas			Electricity		Dry Weight		
Cure	therm NG		gal LP	kWh		lbs	lbs/gal	lbs/kWh	therm NG		gal LP	kWh		lbs	lbs/gal	lbs/kWh
	0			2.83					0			45.22				
1	130	130	357.5	489.21	486.38	2185	6.11	4.49	126	126	346.5	2250.71	2205.49	2194	6.33	0.99
	130			0					126			0				
2	232	102	280.5	842.48	842.48	2128	7.59	2.53	229	103	283.25	906.81	906.81	2138	7.55	2.36
	232			986.45					229			1061.45				
3	348	116	319	2807.23	1820.78	2054	6.44	1.13	340	111	305.25	2928.55	1867.1	2001	6.56	1.07
	348			2807.23					340			2928.55				
4	440	92	253	4328.54	1521.31	3239	12.80	2.13	426	86	236.5	4441.51	1512.96	3122	13.20	2.06
	440			4328.54					426			4441.54				
5	551	111	305.25	5866.86	1538.32	3315	10.86	2.15	528	102	280.5	6004.04	1562.5	3267	11.65	2.09
	551			0					528			0				
6	695	144	396	1773.38	1773.38	3227	8.15	1.82	644	116	319	1884.9	1884.9	3198	10.03	1.70
	695			1773.38					644			1884.9				
7	815	120	330	2099.55	326.17	3199	9.69	9.81	753	109	299.75	3544.8	1659.9	3221	10.75	1.94
	815			2099.55					753			3544.8				
8	930	115	316.25	2648.6	549.05	3427	10.84	6.24	870	117	321.75	4915.93	1371.13	3475	10.80	2.53
	930			2648.6					870			4915.93				
9	1034	104	286	4095.23	1446.63	3451	12.07	2.39	983	113	310.75	6351.45	1435.52	3469	11.16	2.42
	1034			4095.23					983			6351.45				
10	1195	161	442.75	6026.68	1931.45	4063	9.18	2.10	1133	150	412.5	8167.35	1815.9	4090	9.92	2.25
	1195			6026.68					1133			8167.35				
11	1335	140	385	7640.71	1614.03	3522	9.15	2.18	1258	125	343.75	9698.78	1531.43	3445	10.02	2.25
						Average	9.35	3.36						Average	9.81	1.97

SAVINGS							Fan Reduction Notes
Cure	Gas				Normalized Savings		
	therm NG	gal LP	kWh	% Elec.	lbs/gal LP	lbs/kWh	
1	4.00	11	56.39	2.5%	3.6%	-45.3%	Fan turning wrong direction
2	-1.00	-2.75	789.6	46.5%	-0.5%	29.6%	Meter reading incorrectly reset middle of cure
3	5.00	13.75	206.29	9.9%	1.8%	-41.1%	
4	6.00	16.5	183.45	10.8%	3.1%	13.5%	
5	9.00	24.75	133.91	7.9%	7.2%	15.0%	
6	28.00	77	N/A	N/A	23.0%	N/A	Reset after start of cure
7	11.00	30.25	N/A	N/A	10.8%	N/A	
8	-2.00	-5.5	212.87	14.1%	-0.3%	39.4%	Reduced 12% last 48 hours
9	-9.00	-24.75	148.48	9.8%	-7.5%	32.9%	Reduced 12% last 36 hours
10	11.00	30.25	226.5	10.9%	8.0%	23.9%	Reduced 12% first 36 hours Reduced 12% last 48 hours
11	15.00	41.25	240.97	14.2%	9.6%	23.7%	Reduced 12% first 36 hours Reduced 12% last 48 hours

Person County Summary Sheets

	Barn 5 (Check)							Barn 4 (VFD)						
	Gas		Electricity		Dry Weight			Gas		Electricity		Dry Weight		
Cure	gal LP		kWh		lbs	lbs/gal	lbs/kWh	gal LP		kWh		lbs	lbs/gal	lbs/kWh
	1163		0					0		4.405				
1	1248	375.7	N/A	N/A	2335	6.22	N/A	81	358.02	648.3	643.895	2395	6.69	3.72
	1248		373.66					81		8.821				
2	1326	344.76	886.24	512.58	2556	7.41	4.99	164	366.86	655.93	647.109	2493	6.80	3.85
	1326		0					164		0				
3	1400	327.08	605.38	605.38	3250	9.94	5.37	226	274.04	614.45	614.45	3290	12.01	5.35
	1400		651.4					226		614.45				
4	1471	313.82	1309.2	657.8	3317	10.57	5.04	302	335.92	1314.5	700.05	3370	10.03	4.81
	1471		1309.2					302		1314.5				
5	1545	327.08	1985.9	676.7	3671	11.22	5.42	364	274.04	1964.2	649.7	3660	13.36	5.63
	1545		1985.9					364		1964.2				
6	1636	402.22	2668.5	682.6	3712	9.23	5.44	448	371.28	2615.4	651.2	3681	9.91	5.65
					Average	**9.10**	**5.25**					**Average**	**9.80**	**4.84**

SAVINGS						Fan Reduction Notes
	Gas	Electricity		Normalized Savings		
Cure	gal LP	kWh	% Elec.	lbs/gal LP	lbs/kWh	
1	17.68	N/A	N/A	7.6%	N/A	No Reduction
2	-22.1	-134.529	-26.2%	-8.3%	-22.7%	Display Failed at 60 hours
3	53.04	-9.07	-1.5%	20.8%	-0.3%	Display Failed at 48 hours
4	-22.1	-42.25	-6.4%	-5.1%	-4.5%	Reduced 4% leaving 135° Reduced 8% 24 hours later
5	53.04	27	4.0%	19.0%	3.8%	Reduced 4% leaving 135° Reduced 10% 24 hours later
6	30.94	31.4	4.6%	7.4%	3.9%	Reduced 10% leaving 135°

Edgecombe County Summary Sheets

	Barn 15 (Check)							Barn 17 (VFD)						
Cure	Gas		Electricity		Dry Weight			Gas		Electricity		Dry Weight		
	gal LP		kWh		lbs	lbs/gal	lbs/kWh	gal LP		kWh		lbs	lbs/gal	lbs/kWh
	1020		52.5					1089		21.1				
1	1131	490.62	1976	1923.5	3812	7.77	1.98	1195	468.52	1868	1846.9	3665	7.82	1.98
	1131		0					1195		0				
2	1233	450.84	1931	1931	3238	7.18	1.68	1281	380.12	1897	1897	3149	8.28	1.66
	1233		0					1281		0				
3	1337	459.68	1915	1915	3585	7.80	1.87	1369	388.96	1802	1802	3873	9.96	2.15
	1337		1915					1369		1802				
4	1455	521.56	3799	1884	4619	8.86	2.45	1460	402.22	3683	1881	4579	11.38	2.43
	1455		0					1460		0				
5	1570	508.3	2111	2111	4728	9.30	2.24	1558	433.16	1987	1987	4692	10.83	2.36
	1570		2111					1558		1987				
6	1685	508.3	3906	1795	4092	8.05	2.28	1655	428.74	3673	1686	4128	9.63	2.45
					Average	**8.16**	**2.08**					**Average**	**9.65**	**2.17**

SAVINGS						Fan Reduction Notes
Cure	Gas			Normalized Savings		
	gal LP	kWh	% Elec.	lbs/gal LP	lbs/kWh	
1	22.1	76.6	4.0%	0.7%	0.1%	Full Speed
2	70.72	34	1.8%	15.3%	-1.0%	Reduced 5% at 145° on 8/11 Back to 100% on 8/13
3	70.72	113	5.9%	27.7%	14.8%	Reduced 10% on 8/26
4	119.34	3	0.2%	28.5%	-0.7%	Reduced 10% at 160°
5	75.14	124	5.9%	16.5%	5.4%	Reduced 10% at 155°
6	79.56	109	6.1%	19.6%	7.4%	Reduced 10% at 165° with same fan blade