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Energy Efficiency Opportunities for Tobacco Curing Barns

Project: Analysis of energy consumption domains as they occur in the tobacco curing process and assessment of energy efficient retrofit opportunities

Report Type: Technical Assistance Program

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1. Introduction

Tobacco curing is an energy intensive process that has made some progress in automation, but overall has not significantly changed over the past decades.

1.1 Background

While purchasing and installing new barns to replace existing barns is quite expensive, retrofitting existing barns may be a reasonable approach from an investment point. Since many older barns have already significant issues that require attention and retrofit work in terms of structural and safety reasons, this retrofit work can easily be paired with energy efficiency upgraded that can be undertaken at the same time.

Fig 1. Existing, older barn infrastructure shows significant issues that require retrofit actions from a structural and safety perspective

Harvesting the energy saving potential in the process of retrofit actions presents an opportunity to improve the overall performance of tobacco growing operations and at the same time reduces the environmental footprint of this industry.

Little is known about the impact of retrofit scenarios on the actual energy consumption of the curing process. Some easy to use simulation tools have been developed for homeowners and sophisticated simulation models exist for facility managers. However, none of those can be directly applied for the assessment of energy consumption in curing barns. This lack of knowledge creates uncertainty and increases the risks for growers in regards to an anticipated return of investment of more energy efficient solutions that could harvest energy savings during the curing process.

This project attempts to find answers to the following questions:

- How can local growers identify the most energy efficient retrofit scenarios for their specific barn infrastructure
- Is it possible to develop and utilize a simplified energy model specifically for the assessment of curing barns that will achieve a credible level of accuracy and assist growers in the decision-making process towards energy efficient retrofit options?
- Can we identify the most promising retrofit scenarios based on context parameters that can be easily provided by a grower without conducting an on-site audit?
- Can this model be utilized for cost estimates that would later allow growers to assess the return of investment risks of different energy efficient retrofit scenarios?

1.2 Approach

This project investigates the above formulated questions in a systematic, mostly theoretical, and physics based approach.

The total energy consumption of a tobacco curing barn operation during a full curing cycle will be analyzed and broken down by different domains of energy sources, and then further broken down into actual consumption items that utilize certain amounts of energy of a respective domain. This approach will allow us to split possible retrofit scenarios by energy resource and consumption domains, which subsequently will have different impact during different phases of the curing process.

From these findings, we will identify possible retrofit scenarios and compare them among each other for a given context.

2. CONSUMPTION DOMAINS

Tobacco curing is the process of controlled removal of water from tobacco leaves and is considered a craft among growers. In any case, moisture removal is an energy consuming process and thus requires a significant supply of energy, mostly in form of heat.

Historic tobacco curing-barns found in Virginia and North Carolina utilized energy provided by small open fires on the dirt floor of the barn. Later, around 1820, the flue-cure method was introduced for more efficient heating.

Fig 2. Historic tobacco curing barn as it could be found in Virginia and North Carolina in the 19th and 20th century.

Fig 3. Ten year old son of tobacco grower tends a fire which is curing the tobacco in the barn, 1939[1].

Nowadays, curing barns utilize oil or gas fired furnaces supported by an electric powered fan for air circulation and heat exchange with the burner.

Fig 4. Heat exchanger assembly of a gas furnace.

Fig 5. Fan for air circulation and heat exchange

[1] Photo credit: Dorothea Lange

As outlined above the energy sources for the curing process consist of a combination of typically fossil fuels and electricity. Since curing barns are located outside and thus are exposed to direct sunlight during clear days, solar energy could also be utilized to offset some of the required energy for heating.

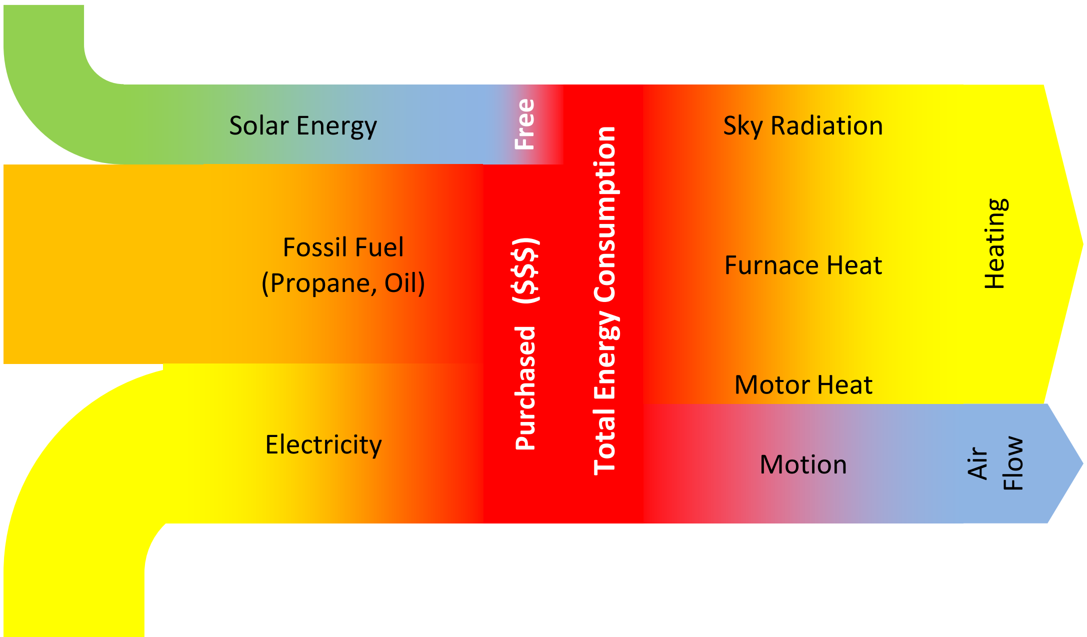

Fig 6. Energy sources of total energy consumption, broken out by process and utilization

2.1 Fossil Fuels

Fuel oil or propane gas, each of which can be stored in tanks nearby, are the predominant energy sources for furnaces in curing barns. Theoretically, heating could also be achieved through electric resistance heating as seen in backup heating systems of residential heat pumps. The obvious advantages would be that electricity is a readily available energy source, which does not require storage capacities on site, and has no associated planning and bulk purchasing processes. But even with some of the nationwide lowest electricity prices the effective associated costs do most probably not outweigh the mentioned advantages.

From a total carbon footprint perspective, electricity would be highly inefficient, since many power plants in southern and western Virginia are coal fired and the conversion process from coal to electricity and the subsequent transportation of electricity have huge (60-70%) associated losses. Depending on furnace technology and equipment maintenance, the actual efficiency of converting fossil fuels into heat energy on site can be quite effective (~90%). If condensing technologies are incorporated into furnace systems, efficiencies can be even further increased.

Interestingly enough, the earlier mentioned historic barns, which were still wood fired, would probably fare best in the carbon footprint race, since wood is considered by some a “renewable” energy source. Obviously the storage requirements and furnace control technologies would raise some questions, but completely automated wood pellet furnaces are meanwhile a serious competitor in residential heating systems around the world.

2.2 Electricity

Historic barns did not have electrical equipment available and thus made use of natural ventilation methods. With the advance of electrical motors and respective fans, curing barns could become more compact, utilize the heated volume more effectively, and drastically reduce the curing time. Packaging densities have been more and more increased, which in return now require more and more energy to overcome friction losses as air is pushed through racks tightly packed with leaves.

While air movement is required to transport moisture from leaves to the exterior, the required energy used for this removal process becomes a function of pressure, air velocity, and moved volumes (flow rate). An optimization function needs to weigh the required electrical energy for air flow to overcome friction losses, against the specific energy consumed by heating the required air volumes per pound of leaves. Obviously, the nature of the leaf drying process and related quality issues set a natural limit to an ever increasing density.

2.3 Solar energy

Solar energy comes into the equation of the curing consumption in form of radiant heat exchange of the exterior barn envelope and its environment. While solar radiation is entirely free and can actively contribute to the required heating energy and thus reduce the fuel consumption during sunny days, any solar gains may be offset by night time sky radiation.

Radiant energy can be exchanged through absorbent surfaces and then be conducted to the opposite surface of a building envelope component. Intuitively it may seem of advantage to increase the absorption coefficient of envelope components in regions with high solar radiation. However, for most materials the absorption coefficient is closely related with a surface's emissivity, its capability to radiate heat off again. Thus in climates with cold night skies, any gains from increased solar absorption during daytime may be offset by night sky radiation losses.

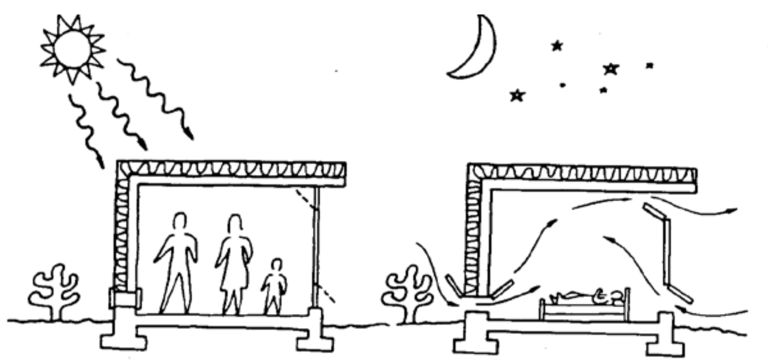

Fig 7. Solar radiation versus night sky radiation needs to be evaluated when looking into harvesting solar energy

Night sky radiation is actively used in hot arid climates to cool down building envelope components during the night. One angle in tweaking an otherwise neutral system at our latitude in favor for heating requirements could be the use of special coatings. Solar radiation comes in high frequencies reaching up into the UV spectrum. Night sky radiation from building components happens typically in the low frequency infrared spectrum. Meanwhile, coatings have been developed that can have different absorption coefficients at different frequencies of the light spectrum.

3. Consumption Processes

3.1 Heating

The heating requirements in the curing process are defined by the following functions:

- Raising the interior temperature to levels that trigger the chemical processes for yellowing and drying. The desired speed for this process defines the upper limit for the required heating capacity of the furnace.
- Maintaining a constant interior temperature over longer periods of time. Depending on the temperature differential between the interior and exterior climate as well as the thermal properties of the materials utilized in envelope components, this process can require significant amounts of energy and defines one part of the lower limit for the heating capacity of the furnace.
- Conditioning make-up air that a) is ventilated off for controlling the interior humidity level, or b) is lost through cracks and openings found in the barn enclosure. Since the drying process releases significant amounts of moisture to the interior climate, the common approach for humidity regulation is releasing a certain amount of hot and humid air and replacing it with drier make-up air. While humidity control is a required process in the curing of leaves, uncontrolled losses through cracks do not necessarily support this process. The heating capacity for providing conditioned make-up air compromises the second part of the minimum requirements of the furnace heating capacity.

In summary, raising the temperature of the interior air volume as well as heating the respective amounts of make-up air as defined by ventilation requirements, is the theoretical minimum of required energy (i.e. utilization). Practically the consumed energy will go beyond this level due to thermal losses through the envelope, energy stored as capacitive heat within construction components such as structural elements of walls and slabs, and exfiltration losses due to uncontrolled ventilation such as air leaks.

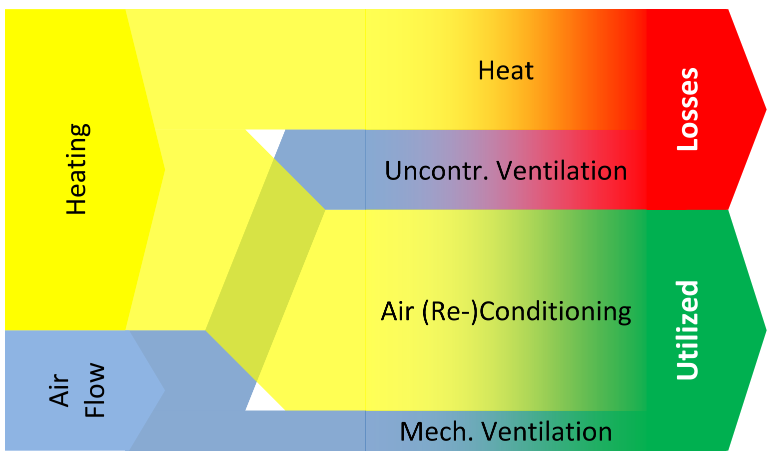

Fig 8. Breakdown of utilization and losses of active processes observed in tobacco curing

Part of the required heating demand is provided directly by the tobacco leaves as they undergo a ripening process where oxidation takes place. Cundiff estimates that the amount of energy released by the leaves can assumed to be around 10% of the required heating energy (Cundiff, The Curing Process 1978). However, this amount was determined to be applicable for experiments conducted at this time and may be a different percentage of the total energy consumption of modern barns.

There is an additional energy flow of that is often overlooked. Any electrical equipment produces significant amounts of process heat. The main function of the involved motors (central fan, inducer motor of furnace) is air movement. At the same time, depending on load conditions, these components can give off significant amounts of heat. Instead of wasting this heat to the exterior, it can be utilized to support the re-heating processes. Since most of these motors depend on air cooling it may not always practical to run (hot) circulation air across the motor windings to support re-heating. However, outside air that needs to be conditioned as make-up air could easily be pre-heated by equipment process heat before it is mixed into the air stream and hits the heat exchanger of the furnace.

Similarly, solar heat can be utilized to pre-heat make-up air by running it through channels below a metal roof. While this technique can support the heating process during sunny days, night sky radiation may actually create more heating demand since it typically cools the air travelling through these channels. A control system similar to an economizer in HVAC systems switching between utilization of channels and bypassing them could resolve this problem and allow for harvesting solar energy. A second function of closed channels during night time could be achieved by utilizing the encapsulated air as an additional insulation layer similar to air gaps in window systems.

3.2 Air flow and Ventilation

Air movement has three core functions in the curing process:

- First and most obvious for growers, adequate airflow is necessary for high quality cures that will trigger the desired chemical processes in leaves.
- Second, certain amounts of airflow are utilized to remove excess moisture from the interior environment, typically referred to as ventilation rate. While ventilation in building systems is mostly used for indoor air quality (i.e. removal of pollutants and carbon monoxide exhaled by its occupants) the ventilation system in curing barns controls for a steady relative humidity level during the respective stages of the curing process.
- Third and probably less obvious for observers, air flow is the actual means to transport heat from the furnace to the main curing compartment holding the stacked leaves. This is achieved in convection processes of air passing over coils of a heat exchanger, which is then moved into the curing chamber, and then recirculated for reconditioning.

In summary, mechanical fans are utilized to actively convey heat from the furnace to the air stream through convection, then move the heated air to the curing chamber, and remove excessive moist air from the interior environment. These utilization functions define the theoretical minimum energy requirements for air flow processes in curing barns. Naturally, the actual consumption is somehow higher due to losses resulting from friction and uncontrolled air leakage.

The interrelated dynamics of air flow and heating processes make projections of overall energy consumption complex. For example, higher velocities typically create more convection along surfaces. While this is a desired effect for the heat exchanger, higher convection along transportation channels also creates higher heat losses across ducting surfaces and its respective material layers. More attention to insulation strategies in high velocity ducting areas may be one option to tackle this issue.

Besides higher heat losses from higher convection rates, increased velocity also creates higher friction in ducting systems, which in turn requires a higher pressure to be built up by the fan to overcome these friction losses, which subsequently draws more electrical power. Furthermore, higher duct pressure increases exfiltration rates across leaks, which then again require more energy for re-conditioning make-up air. The overall goal in this process is to strike a balance of large enough profile cross section areas to reduce velocities in ducting channels while keeping the overall losses due to increased surface areas to a minimum.

4. Energy Analysis

The following section will break down the utilization and losses of the different energy consuming processes as they occur in tobacco curing cycles.

Specific modeling equations will be established that will allow for a simplified assessment of the different consumption streams as shown in Fig 9. The following energy streams have been identified: drying (dehumidifying) the leaves; raising the interior temperature of the barn during different curing phases; maintaining temperatures due to conduction losses and leaks; process control and waste; and systems performance and maintenance.

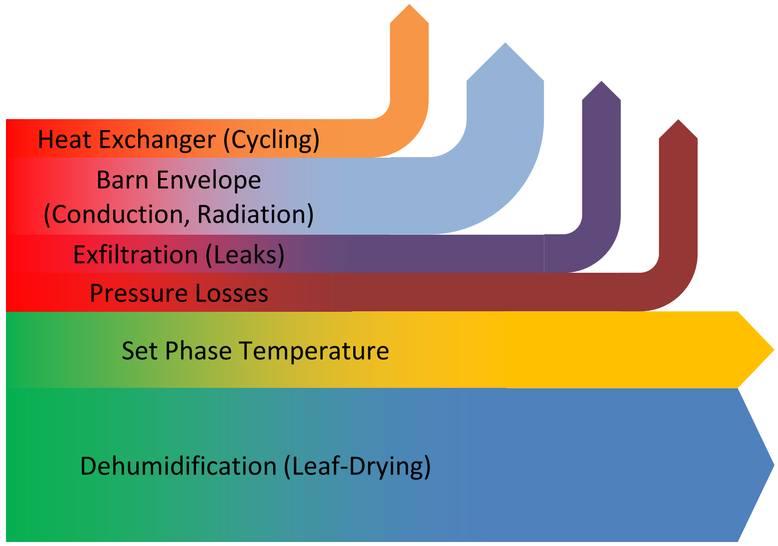

Fig 9. Breakdown of utilization and losses of active processes observed in tobacco curing

4.1 Energy Consumption of the Heating process

The scheduled temperature levels in curing barns during the curing process are well above ambient temperatures. Fig 10 shows typical dry bulb temperatures that must be maintained during a curing process according to different sources. Some variations can be observed, with slightly higher recommendations in more recent publications, specifically during the stem-drying phase, which occurs in the last two days of the cycle.

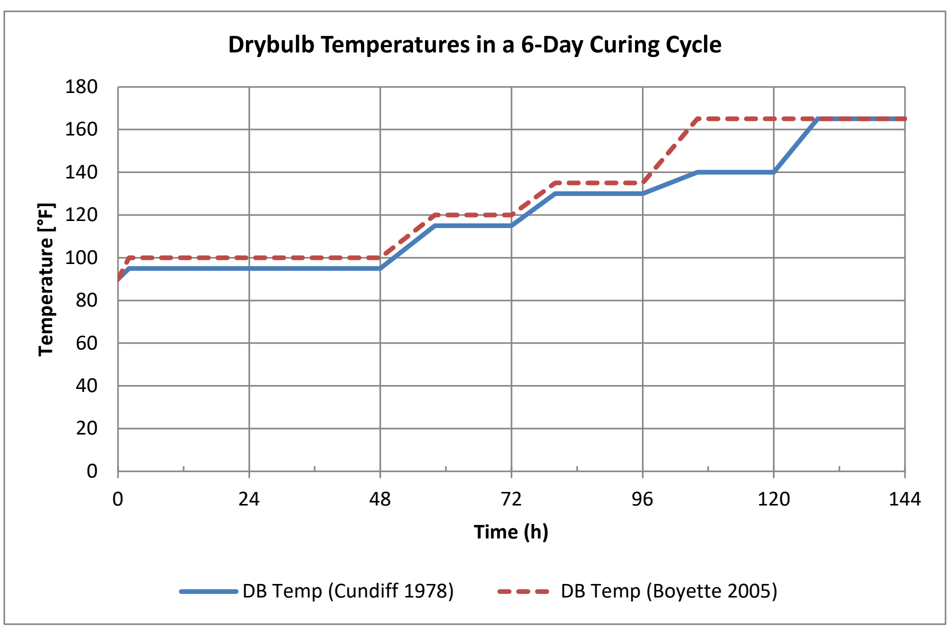

Fig 10. Drybulb temperatures in curing cycles according to different sources

4.1.1 ENERGY REQUIREMENTS FOR HEATING

As outlined in the previous section, energy in form of heat is required to raise and maintain the dry bulb temperature to certain levels throughout a curing cycle. This type of energy is referred to as sensible (temperature related) energy and can be described through the following equation:

$$Q_s = m \cdot c_{pa} \cdot \Delta t \qquad \textit{Eq. 1}$$

where:

Q_s = the sensible heat energy in [BTU]
m = the specific mass of air in [lb]
c_{pa} = the specific heat capacity of air in [BTU/lb.°F]
Δt = the change of dry bulb temperature in [°F]

The specific heat capacity at standard atmospheric sea level pressure (1 atm) at room 20°C would be 0.2403 Btu/lb°F. For our application we can assume it with

$$c_{pa} = 0.24 \frac{BTU}{lb \cdot F} \qquad \textit{Eq. 2}$$

Since we do not want to measure the weight of our air but rather its volume, we calculate the mass from the density of air. For our pressure and temperature range with assume it with 0.075 lb/cf, and can re-write Eq. 1 as follows:

$$Q_s = 0.075 \cdot 0.24 \cdot V_a \cdot \Delta t \qquad \textit{Eq. 3}$$

where:

Q_s = the sensible heat energy in [BTU]
V_a = the volume of the air to be heated in [cf]
Δt = the change of dry bulb temperature in [°F]

For example, raising the volume of one of the investigated barns (Type Powell ~3500 cf) from an ambient 80°F to 100°F would require

$$Q_s = 0.075 \cdot 0.24 \cdot 3500 \cdot 20 = 1260 \text{ BTU}$$

4.1.2 ENERGY LOSSES DURING HEATING

Unfortunately, some of the heat provided to a barn is continuously lost through heat exchange processes with its environment. The largest amount of these losses will occur in form of conduction losses.

Energy losses through conduction also referred to as transmission losses can be captured through the following equation:

$$Q_t = \sum U_i \cdot A_i \cdot \Delta t \cdot d \qquad \textit{Eq. 4}$$

where:

Q_t = the transmission heat losses in [BTU]
U_i = the individual thermal conductance of a building component enclosing the conditioned space in [BTUh/sf·°F]
A_i = the individual area of the building component in [sf]
Δt = the temperature difference between the ext. and int. air in [°F]
d = the duration of this condition in [hr]

This equation sums the individual products of respective enclosure areas, conductances, and boundary conditions, as well as their duration. Obviously this is an amount of energy that needs to be consistently provided to maintain a desired interior temperature. The better insulated a barn, the smaller these losses will become.

For example, if we for now assume a uniform envelope construction with a U-Value of 0.3 BTUh/sf·°F, and the total surface area of the enclosure would come to 1500 sf, we can calculate the energy consumption for the first yellowing phase (2 days) with

$$Q_t = 0.3 \cdot 1500 \cdot 20 \cdot 48 = 432{,}000\ BTU \qquad \textit{Eq. 5}$$

Besides conduction losses, there are also capacitive losses, which go mostly into the slab, and other structural heavy elements. However, in a barn with an insulated slab, the capacitive losses can be estimated to be less than 5% of the total heat losses, and thus can for now be neglected for our modeling approach (Cundiff, Structural Heat Loss Influence on Curing Efficiency 1978).

Finally, there is also significant radiant exchange with the environment in form of solar gains and night sky radiation. However, unless a special radiant absorption and emission system is installed, solar gains and night sky losses will more or less cancel each other out (Cundiff, Structural Heat Loss Influence on Curing Efficiency 1978) and will thus for now be neglected in the overall assessment model.

> As can be seen easily by these examples, the amount of energy required to reach a higher temperature level is relatively small compared to the amount it takes to maintain this temperature.

4.1.3 Preliminary Experimental Tests for Heat Load Comparisons

Preliminary thermal capacity tests carried out at a single farm demonstrate the various thermal losses over time under non-loaded conditions. Fig 13 provides an overview of the tests conducted on June 5, 2013 in Vernon Hill, VA. The first test was run with Powell barn, which is about 10 to 12 years old, is set on an insulated concrete slab, and shows continuous insulated walls, doors, and roof elements. Later that day, tests were continued with an older Roanoke barn. Initially the burner of this barn wouldn't fire correctly and it took a service crew several hours to identify and remedy a faulty gas valve. Ultimately the load test could be started shortly after 4:30pm at observed for around 60 minutes to follow and record the cool-off phase.

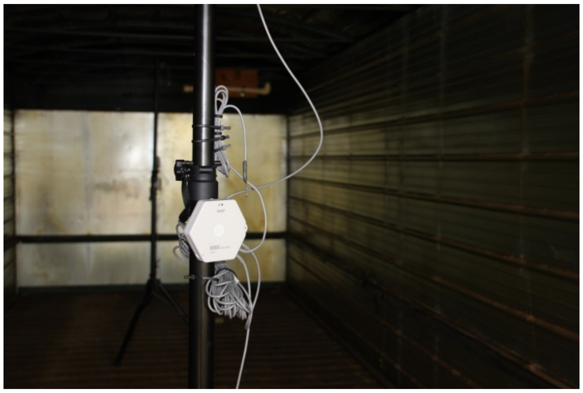

Fig 11. Two poles with temperature probes were placed within the curing compartment of the empty barn

Fig 12. The central sensor recorded temperature and relative humidity, top and bottom sensors were temperature only.

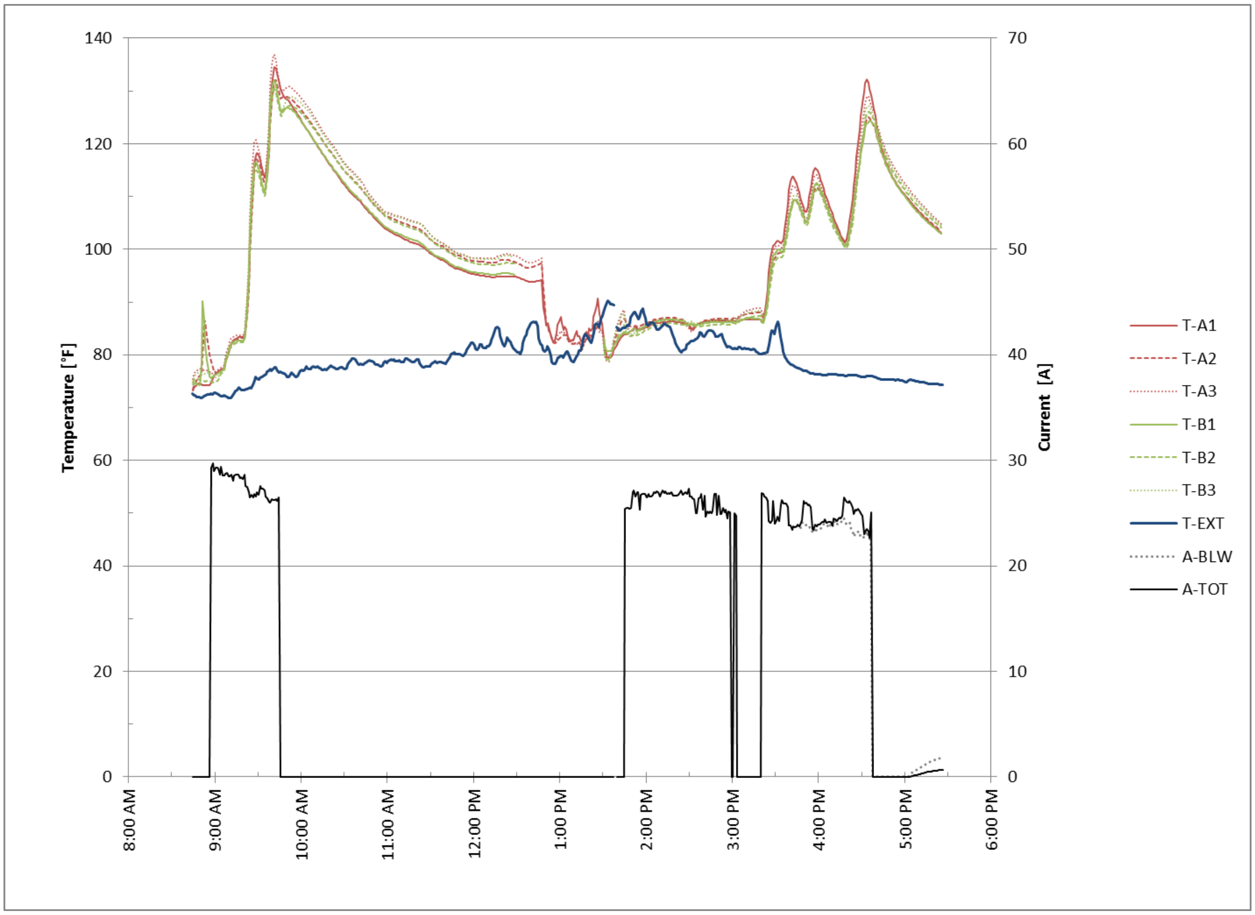

Fig 13. Overview of experimental data collection during tests on June 5, 2013. The first test carried out between 9am and 1pm was a load test on a Powell barn, the second test, ultimately started around 3:30pm was on a Roanoke barn.

The barns were empty and only equipped with temperature sensors located in the inside and current loggers connected to the electrical panel. From Fig 13 it can be easily seen, when the fan and furnace were actually running.

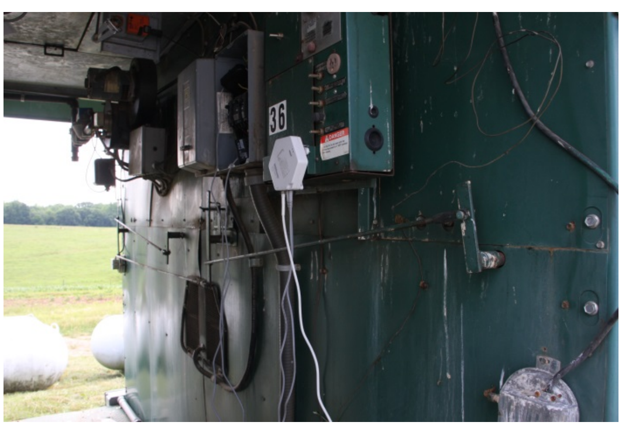

Fig 14. A second wireless node was used to collect ambient temperature and humidity conditions

Fig 15. Two current transducers measured total current and motor current respectively

Each test was scheduled to first heat up to a set-point temperature of 140°F (a temperature limit of the utilized equipment) with a subsequent shut off of all systems (fan and furnace off) only monitoring the drop of temperatures. The following observations can be derived from these tests:

- Neither of two barns reaches the actual set-point temperature of the interior climate as adjusted through the control panel. The system used in the Powell barn comes somehow closer, while the system in the Roanoke barn indicated to have reached the set point temperature much earlier.
- Though the tests on the second barn could not run for the same time, it still became evident that heat transmission losses without insulation have a significant impact on the rate of temperature losses.
- Since those tests were conducted with rapid changes of temperature, capacitive heat transfer becomes a larger factor in "buffering" heat (first absorbing, and then releasing again). In other words, the actual drop of temperature would be more significant if absorbed capacitive heat from the slab would not be released to the space again. Practically this exchange does not have a great impact during curing processes, since most stages of the curing process are kept at a steady state temperature level.

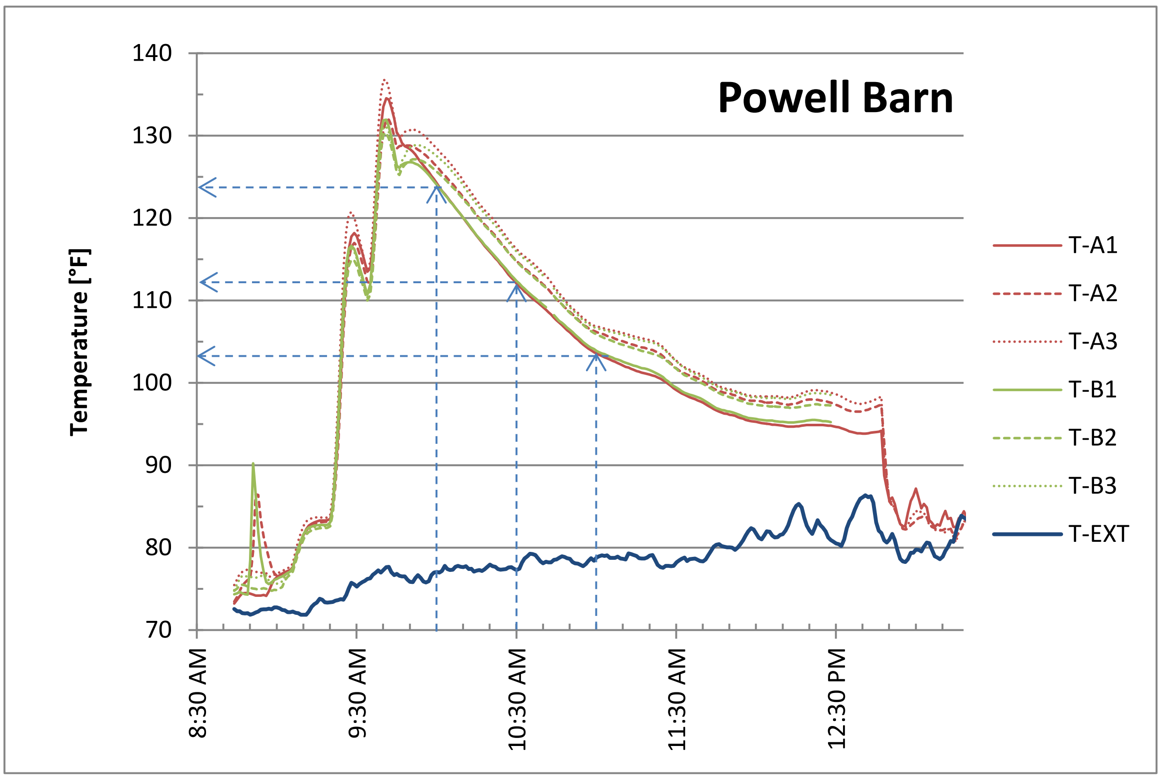

Fig 16. Heat load profile of an insulated newer barn, with initially controlled temperature rise, and subsequent fast rise to set point temperature

Originally it was envisioned to obtain overall conductive transmission loss numbers from these experiments. With the short term influence of capacitive changes this cannot be achieved with sufficient accuracy. Nevertheless, these tests will utilized as a comparative baseline scenarios for future retrofit options as well as comparative studies with tests conducted on fully loaded barns.

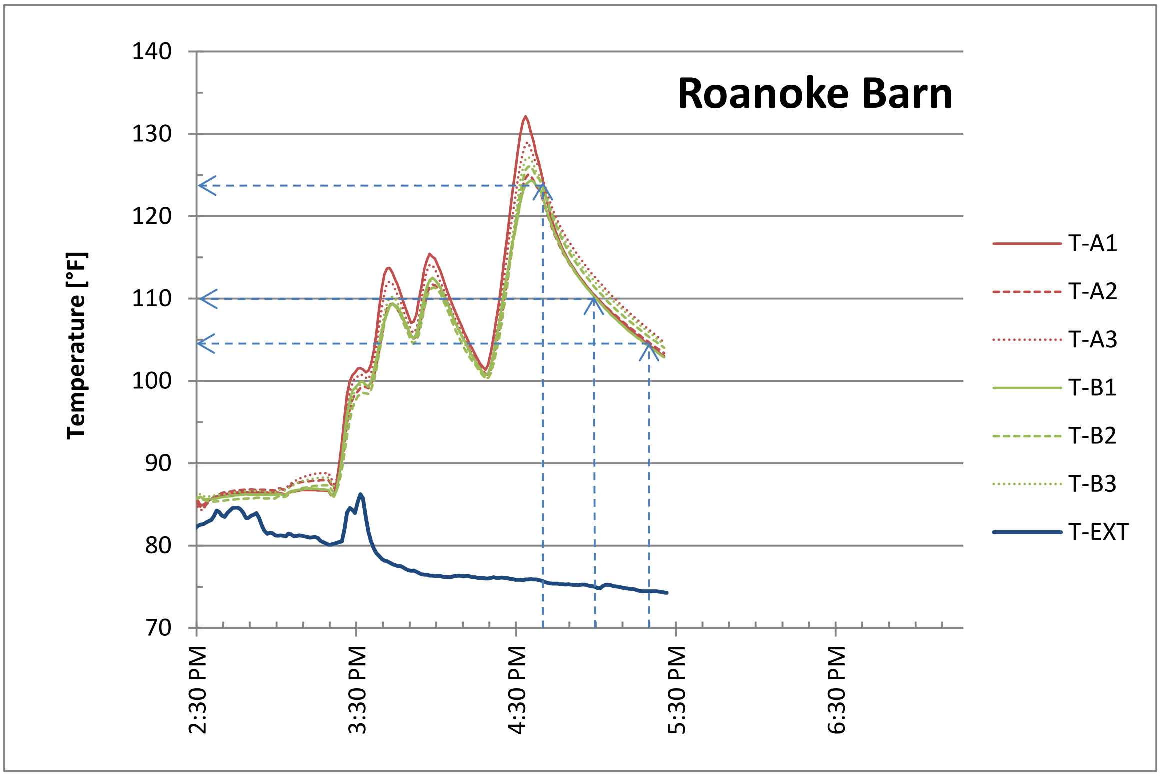

Fig 17. Heat load profile of non-insulated older barn, showing initial furnace issues before running up to the set point temperature.

In addition to the temperature profiles, velocity tests were carried out to assess basic supply and return flow rates (Fig 18 and Fig 19). These tests were preliminary conducted as reference velocities for comparison with fully loaded barns. A more comprehensive flow rate profile will have to be established to derive actual infiltration loss rates as they occur during operation.

Fig 18. Central velocity in supply plenum between heat exchanger and curing compartment

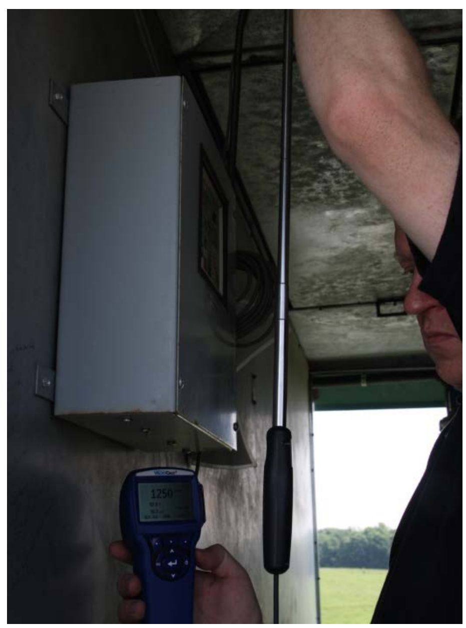

Fig 19. Velocity in the return plenum leaving the curing compartment

4.2 Energy Consumption of the dehumidification Process

When air is heated, the relative humidity typically drops, as warmer air can hold (relatively) more moisture. However, due to the ongoing evaporation processes (i.e. drying of leaves) within the barn the absolute humidity level will continuously increase and relative humidity must be controlled for by ventilation.

Fig 20 shows typical relative humidity levels, which were calculated from dry-bulb and wet-bulb temperature schedules that must be maintained during the curing process according to different sources. Some variations can be observed, with slightly lower relative humidity level recommendations in more recent publications.

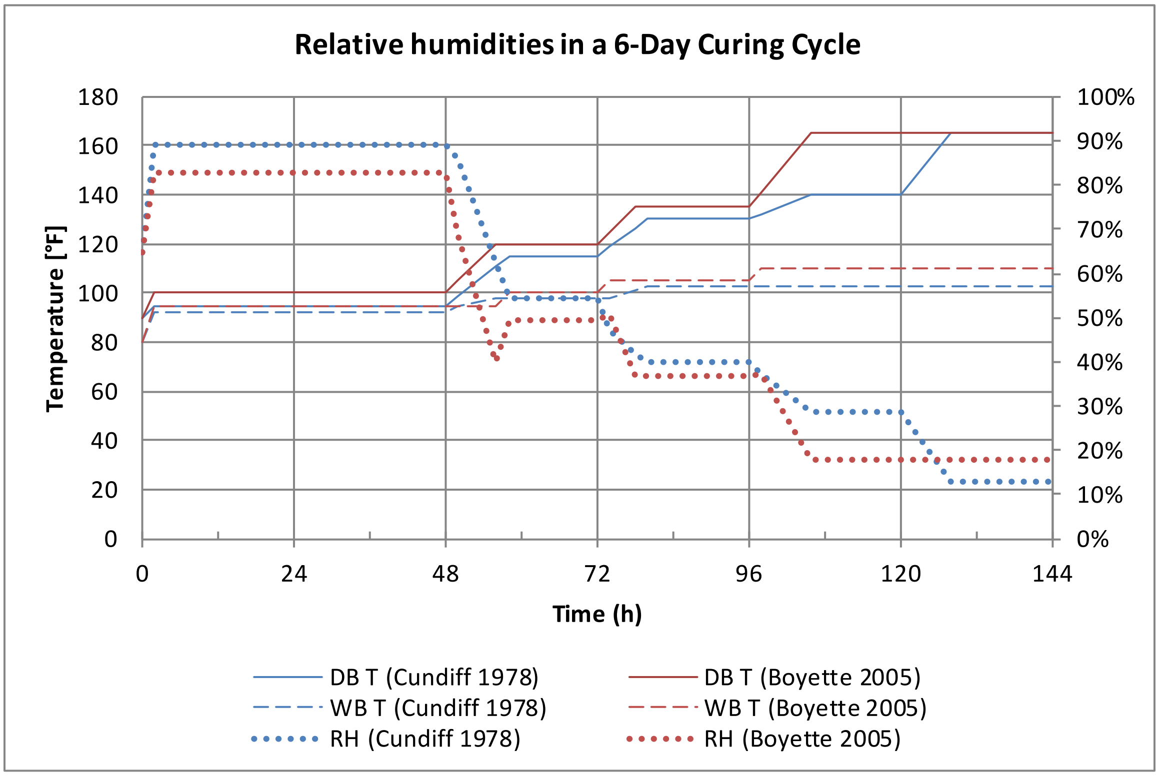

Fig 20. Resulting relative humidity levels over the various curing cycles calculated from dry-bulb and wet-bulb temperature schedules as provided by different sources.

4.2.1 Energy Requirements for Dehumidification

Higher temperatures within the barn increase the evaporation process along leaf surfaces, which in turn creates higher levels of humidity in the interior air. Dehumidification of the interior air is achieved through ventilation by replacing highly humid air with less humid air. The phase change from liquid to gas – here water to vapor – absorbs energy in form of latent heat and is therefore cooling its surroundings. The absorbed energy is stored in form of capacitive heat in the vapor dispersed in air. This type of energy is referred to as latent (phase change related) energy and can be described through the following equation:

$$Q_l = m \cdot h_{we} \qquad \textit{Eq. 6}$$

where:

Q_l = the latent heat energy absorbed/released in [BTU]
m = the specific mass of evaprotated water in [lb]
h_{we} = the specific latent heat for water [BTU/lb]

For our purposes, we want to know how much heat energy is absorbed by the evaporation process that then needs to be added again in form of sensible heat by the furnace. We can calculate the mass through the interior volume of air and the weight of water that gets absorbed as the humidity level increases:

$$Q_l = h_{we} \cdot \rho \cdot q \cdot \Delta x \qquad \textit{Eq. 7}$$

or

$$Q_l = 1060 \cdot 0.075 \cdot V \cdot \Delta x \qquad \textit{Eq. 8}$$

where:

Q_l = the latent heat energy absorbed/released in [BTU]
h_{we} = the specific latent heat for vaporization of water in [BTU/lb]
ρ = the density of air under standard conditions in [lb/cf]
V = the volume of the observed air in [cf]
Δx = the difference of humidity ratio in [lb/lb]

The humidity ratio is defined as the actual weight of water in air per pound of dry air [lb/lb]. The different humidity ratios can be calculated from observed dry bulb and wet bulb temperatures or respective relative humidity values. For these calculations we convert to SI units, since the utilized equations are temperature dependent and Fahrenheit and Celsius do not share a common value of zero. With

$$T_C = (T_F - 32) \cdot \frac{5}{9} \qquad \textit{Eq. 9}$$

we can calculate the saturation pressure (under which condensate occurs) in [hPa] of air at this temperature

$$p_s = 6.112 \cdot e^{\left(\frac{17.67 \cdot T_C}{T_C + 243.5}\right)} \quad \text{[hPa]} \qquad \textit{Eq. 10}$$

The actual vapor pressure can then be determined by the current relative humidity:

$$p_w = p_s \cdot RH \quad \text{[hPa]} \qquad \textit{Eq. 11}$$

And the humidity ratio finally is then defined as:

$$x = 0.622 \cdot p_w / (p_a - p_w) \qquad \textit{Eq. 12}$$

where:

x = the humidity ratio of air in [lb/lb]
p_w = the vapor pressure of air under actual temperature conditions [hPa]
p_a = the ambient atmospheric pressure in [hPa] here assumed with 1013.25 [hPa]

For example, the humidity ratio of exterior air at 75°F and 80% RH would be calculated by converting the temperature into 23.9°C, resulting in a saturation pressure of 29.63 hPa and actual vapor pressure of 23.71 hPa. From Eq. 12 we would then get a humidity ratio x of 0.0149 lb/lb. Similarly, the humidity ratio of interior for air during the yellowing phase with 100°F DB and 83% RH would be calculated as 0.0353 lb/lb. The energy required to raise the humidity level of the interior volume from ambient levels to the yellowing phase level could then be calculated from Eq. 8.

Since we do not directly know the weight of the air in our barn, but rather its volume, the humidity ratio doesn’t answer how much water the interior air volume can actually hold. The amount of water in a specified volume of air is called absolute humidity, which is defined as weight of water vapor per volume of (moist) air. The absolute humidity can be calculated from the saturation pressure and the humidity ratio

$$a = 216.679 \cdot p_w/(T + 273) \quad \textit{Eq. 13}$$

where:

a = the absolute humidity in [g/m]
p_w = the vapor pressure in [hPa]
T = the temperature in [°C]

Or converted back to imperial units

$$a = \frac{0.062428}{1000} \cdot 216.679 \cdot p_w/(T + 273) \quad \text{[lb/cf]} \quad \textit{Eq. 14}$$

Outside air of 75°F and 80% RH will have an absolute humidity of 17.3 g/m³ or 0.00108 lb/cf. Interior air (100°F / 83% RH) will have an absolute humidity of 37.96 g/m³ or 0.00237 lb/cf. For example, a barn with 3000 cf of interior volume and the above listed climate conditions, which are typical during the yellowing phase, could absorb 0.00129 lb/cf, or 3.87 lb.

Obviously, the amount of water to be evaporated from leaves will by far exceed the absorption capacity of a single interior air volume. Thus humid air is ventilated and new dryer make-up air is brought into the barn. The question now arises, how much make-up air is required to absorb the amount of water that needs to be extracted from the leaves during a certain curing phase.

From knowing the total weight of green leaves, and estimating its total moisture content (around 90% for lower stalk tobacco and around 80% for upper stalk tobacco) we can calculate the volume of make-up air that is required to absorb and ultimately remove the total amount of evaporated water.

$$V_{ex} = m_{lf} \cdot w/\Delta a \quad \textit{Eq. 15}$$

where:

V_{ex} = the required exchange volume in [cf]
m_{lf} = the weight of loaded tobacco in [lb]
w = the water content of the leaves in [%]
Δa = the difference in absolute humidity between exterior air and exhausted air in [lb/cf]

Since the interior climate is not constant, but rather changes by following a curing schedule, we need to split the different amounts of moisture to be evaporated and removed by each curing phases and build the total sum of the individual parts.

$$V_{ex} = \sum_p m_{lf} \cdot w \cdot e_p/\Delta a_p \quad \textit{Eq. 16}$$

where:

m_{lf} = the weight of loaded tobacco in [lb]
w = the water content of the leaves in [%]
e_p = evaporation ratio of phase in [%] (total of all ratios must equal 1)
Δa_p = the difference in absolute humidity during the phase in [lb/cf]

For example, to remove 30% of water during the first two days in the yellowing phase, a barn loaded with 20,000 lb of lower stalk tobacco (90% water content), must remove 5,400 lb of water. Using the above introduced absolute humidity differential this would require to exhaust and subsequently recondition an exchange volume of more than four million cubic feet of air.

$$V_{ex} = 20{,}000 \cdot 0.90 \cdot 0.30/0.00129 = 4{,}186{,}000 \text{ cf} \qquad \textit{Eq. 17}$$

For a barn with curing chamber size of 3,000 cf, this would translate to around 1,400 complete air changes during this period (48h), or roughly 30 air changes per hour (ACH).

The total required energy for dehumidification (ventilation) is the sum of the latent energy required to absorb the evaporated water in form of vapor during each curing phase

$$Q_l = 1060 \cdot 0.075 \cdot \sum_p V_{ex,p} \cdot \Delta x_p \qquad \textit{Eq. 18}$$

where:

$V_{ex,p}$ = the exhausted volume during phase p in [cf]
Δx_p = the difference in humidity ratio during phase p in [lb/lb]

plus the sensible energy required to recondition the make-up air to the required interior temperature level:

$$Q_s = 0.075 \cdot 0.24 \cdot \sum_p V_{ex,p} \cdot \Delta T_p \qquad \textit{Eq. 19}$$

where:

ΔT_p = the difference in temperature during phase p in [lb/lb]

$$Q_v = Q_s + Q_l \qquad \textit{Eq. 20}$$

Not all of this energy needs to be provided by the furnace since tobacco curing is a chemical process where oxidation occurs. This oxidation process as well as local condensation with water fallout of highly humid air along colder surfaces provides energy gains that subset the overall energy requirements for dehumidification in the curing process. Detailed information and test data of how much energy is released during tobacco curing was not at hand to be utilized for this study. However, past research has shown that the average energy to evaporate water from tobacco leaves can be assumed around 1,100 BTU/lb. The required energy for dehumidification can then be simplified calculated from:

$$Q_d = m_w \cdot c_e \qquad \textit{Eq. 21}$$

where:

Q_d = the overall energy required for vaporization in [BTU]
m_w = the amount of water to be removed in [lb]
c_e = the specific evaporation energy coefficient of 1,100 [BTU/lb]

4.2.2 Energy Requirements for Mechanical Ventilation

Since natural convection would not create sufficient air flow for ventilation and recirculation, all modern curing barns utilize a fan for controlled air movement in the curing chamber. The energy required for this fan is typically provided in form of electricity and can be calculated from the following equation:

$$Q_e = 3412 \cdot \int P_e \cdot dt \qquad \textit{Eq. 22}$$

where:

Q_e = the electrical energy consumed converted into [BTU]

P_e = the electrical power consumed at a given time in [kW]
dt = the elapsed time in [hr]

The actual power consumed by the fan will depend on the pressure the fan needs to overcome for circulating air at a given speed. This pressure drop is a combination of friction losses across the supply and return channels within the barn, and more importantly the resistance that develops as air is pushed through densely packed tobacco leaves. Once the leaves start to dry the actual density shrinks and the resistance decreases resulting in higher air flow velocities. For this reason the power consumed by the fan will vary over a curing cycle but can be easily measured by the drawn current for a given voltage and known power factor of the motor.

$$Q_e = 3.412 \cdot E \cdot \varphi \int I_e \cdot dt \qquad \textit{Eq. 23}$$

where:

Q_e = the electrical energy consumed converted into [BTU]
E = the electromotive force (line voltage) in [V]
φ = the power factor of the motor
I_e = the electric current at a given time in [A]

A fan running on a line voltage of 230V and a power factor of 80% drawing 20 A of current on average would consume

$$Q_e = 3.412 \cdot 240 \cdot 20 \cdot 0.8 \cdot 144 = 1{,}808{,}100 \ BTU \qquad \textit{Eq. 24}$$

when running constantly over a 6 day curing period.

4.2.3 Energy Losses During Dehumidification

As losses of the dehumidification process we can consider any consumption that does not directly contribute to remove moisture.

Any exterior air that is conditioned (heated) as it is brought into the barn and then not absorbing moisture before it leaves the barn, e.g. through leaks in the supply plenum, needs to be replaced by make-up air, which again needs to be re-heated. These losses are called infiltration losses and can be captured by the sensible heat that is removed from the barn. Infiltration rates are typically measured as volumetric air change rates per hour. Since this is once again an air flow that can be quantified in volumes, we can re-write Eq. 3 for this energy stream and get

$$Q_i = 0.075 \cdot 0.24 \cdot V_{int} \cdot ACH \cdot \Delta t \cdot d \qquad \textit{Eq. 25}$$

where:

Q_i = the infiltration losses in [BTU]
V_{int} = the interior air volume [cf]
ACH = the air change rate [1/h]
Δt = the temperature difference in [°F]
d = the duration of the process

For example, if we assume an ACH of 0.5 for a volume of 3500 cf, an ambient temperature of 80°F, and a set-point temperature of 120°F, the consumption over a 48h period would come to

$$Q_i = 0.075 \cdot 0.24 \cdot 3500 \cdot 0.5 \cdot 40 \cdot 48 = 60{,}480 \text{ BTU.}$$

The same approach can be utilized for losses resulting from over-ventilation. If interior air is ventilated before it has absorbed enough humidity (up to the target level) as specified by the schedule, then this volume has been heated to the set-point temperature but missed out on moving water out of the barn. In an initial modeling approach these losses can be defined as a percentage of the total ventilation requirement:

$$Q_{v,l} = 0.075 \cdot 0.24 \cdot \sum_{1}^{p} V_{exh,p} \cdot LF_p \cdot \Delta t_p \qquad \textit{Eq. 26}$$

where:

$Q_{v,l}$ = the losses from over ventilation in [BTU]
$V_{exh,p}$ = the exhausted air volume in a phase [cf]
LF_p = the loss factor during the phase in [%]
Δt_p = the temperature difference during the phase in [°F]

4.2.4 Equipment Energy Losses

Ultimately there will also be losses on the equipment side such as furnace efficiencies that can vary dramatically if proper maintenance has been neglected. For this preliminary study the furnace efficiency will be assumed with 90%.

Short term cycling rates of control equipment can also lead to additional operational losses, since a heat exchanger reaches its specific heat transfer capacity only after a certain lead time. For this stage of the investigation, we assume a properly sized and well-tuned furnace that will not undergo unreasonable cycling during the different curing phases.

5. Discussion

5.1 Baseline Scenario

A theoretical study of energy consumption broken down by curing phase and consumption domain has been conducted. The baseline model is based on a curing barn with a total interior volume of 3,500 cf and about 3,000 cf in the curing space. The barn is assumed to be filled with 15,000 lbs of tobacco leaves with a moisture content of 85%. This requires the removal of 12,750 lbs of water resulting in 2,250 lbs of dry leaves after drying. Assuming 15% of solid loss and ordering the leaves back to 20% moisture content, will leave the grower with 2,390 lbs of cured tobacco.

We furthermore assume a constant average ambient climate of 75°F and 80% RH, which is a typical average for Danville, VA in August. The average ground temperature is assumed with 60°F.

The thermal baseline resistances of the envelope are assumed with R=3 $ft^2 \cdot °F/BTUh$ for the non-insulated roof and walls, and R=2 $ft^2 \cdot °F/BTUh$ for the resistance of the slab to the ground.

The initial leakage rate is set to 5 ACH, which is assumed to be typical for older barns with worn out washers around doors and visible corrosion holes along the perimeter of the supply plenum. Finally, we assume an average over-ventilation rate of 30% across all phases, which can occur if no automated control system is engaged.

5.2 Comparison by Consumption domain

5.2.1 Baseline Consumption

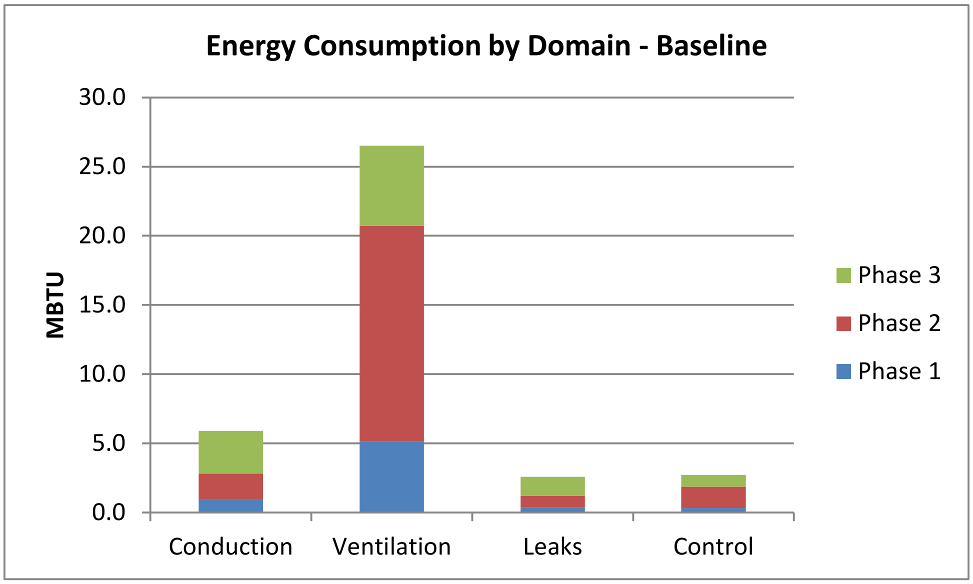

Fig 21. Total energy consumption of tobacco curing broken down by consumption domains.

For the baseline scenario as described in 5.1 the energy amounts consumed by the different consumption domains as lined out in sections 4.1 and 4.2 would then come out as shown in Fig 21. The by far largest consumption domain is the one involving the dehumidification and ventilation processes, followed by thermal conduction in form of transmission losses through the barn envelope. Leakage was assumed at 5 ACH for the baseline, which would make the respective consumption about half of those associated with conduction. Furthermore, an over-ventilation rate of 30% across all phases was assumed for this baseline scenario, resulting in similar energy loss as calculated from leaks.

Grouping the different consumption amounts by curing phase (compare Fig 22), we can see that the two days of the leaf-drying phase are the days of the highest energy consumption of the entire curing cycle. It is also interesting to observe that the larger amounts of latent heat in the humid but cooler air exhausted during the yellowing phase are about the same as the lower amounts of latent heat in the warmer dry air exhausted during the stem-drying phase. Furthermore, we can confirm that transmission losses as expected increase with greater temperature differentials in each consequent phase. During stem-drying phase the conduction losses can then represent up to a third of the total energy consumption during this phase.

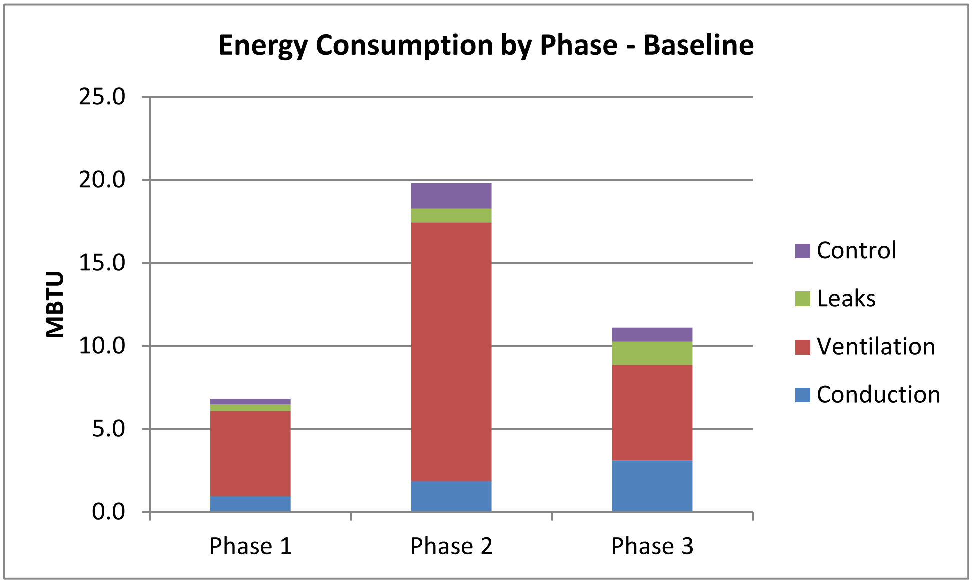

Fig 22. Total energy consumption of tobacco curing broken down by curing phases. Phase 1 – Yellowing, Phase 2 – Leaf Drying, Phase 3 – Stem Drying

5.2.2 Envelope Improvements

As a first possible retrofit scenario we investigated improvements to the barn envelope. In particular we assumed an improved thermal resistance for the barn roof and walls, as it could be achieved by adding spray foam or insulation boards into the envelope cavities. Two layers of ¾" foam boards could yield a theoretical resistance improvement of 7-8 $ft^2 \cdot °F/BTUh$. Practically, mostly due to thermal bridges around studs and other structural elements, a total R-Value improvement of 4-5 $ft^2 \cdot °F/BTUh$ is more realistic.

A second step in envelope improvement would be a careful sealing of all uncontrolled air flow openings. If applicable spray foams are utilized for insulating the cavities, they typically also provide excellent results in respect to envelope tightness. Alternatively sealants can be used along all seams and edges to cut down on infiltration losses. Special attention should be paid to holes resulting from corrosion along the subfloor (supply plenum) perimeter. This retrofit approach will not only theoretically eliminate infiltration, but can also practically result in the successful reduction of uncontrolled ventilation to a negligible minimum by easy to use means.

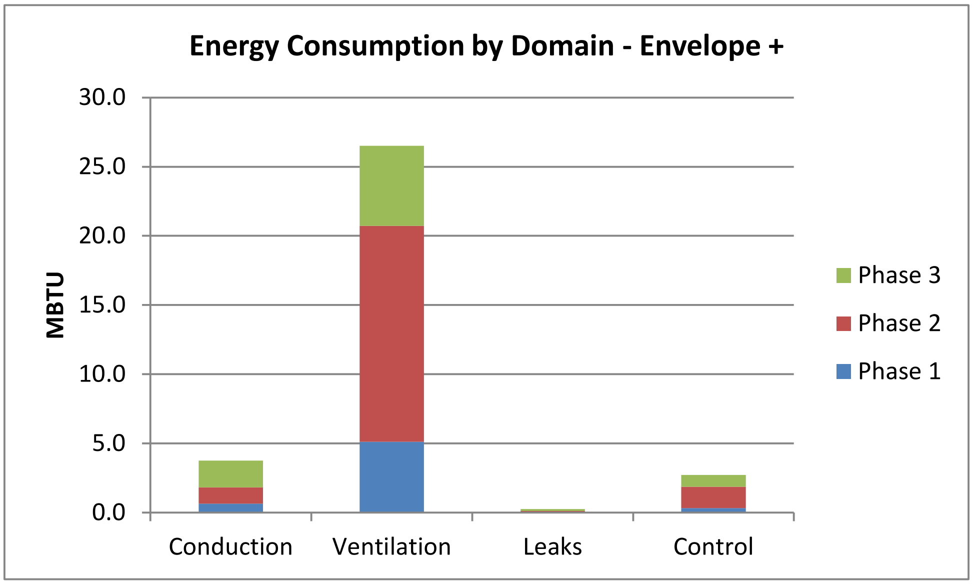

Fig 23. Total energy consumption after retrofit scenario "Envelope +" has been applied. Infiltration leaks can practically be eliminated and conduction losses can be reduced

Fig 23 shows again the energy consumption broken down by domain. The results show the energy reduction as achieved by increasing the wall resistance to 7 $ft^2 \cdot °F/BTUh$ and the roof resistance to 8 $ft^2 \cdot °F/BTUh$ respectively. Infiltration rates have been assumed to be reduced to 0.5 ACH, a value that regular residential buildings have, and thus is definitely achievable. While the reduced infiltration rate practically eliminates leakage losses, the thermal transmission losses are reduced by around 35%. In total, this retrofit scenario could yield about 12% of energy savings overall (Fig 24).

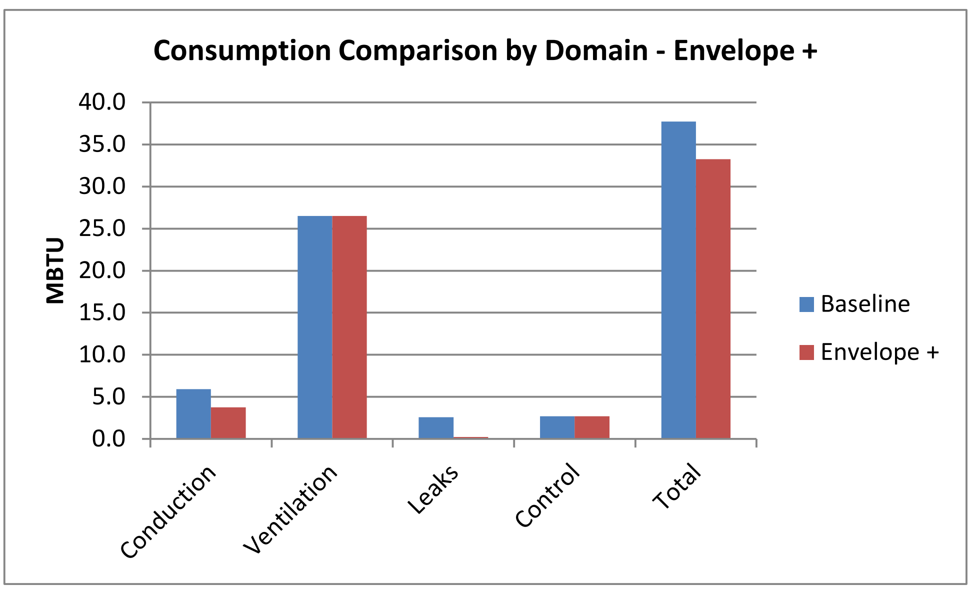

Fig 24. Comparison of energy consumption of retrofit scenario "Envelope +" and baseline scenario by consumption domain

As shown in Fig 25, the larger bulk of consumption savings is achieved in the later phases since both affected consumption domains are temperature differential dependent.

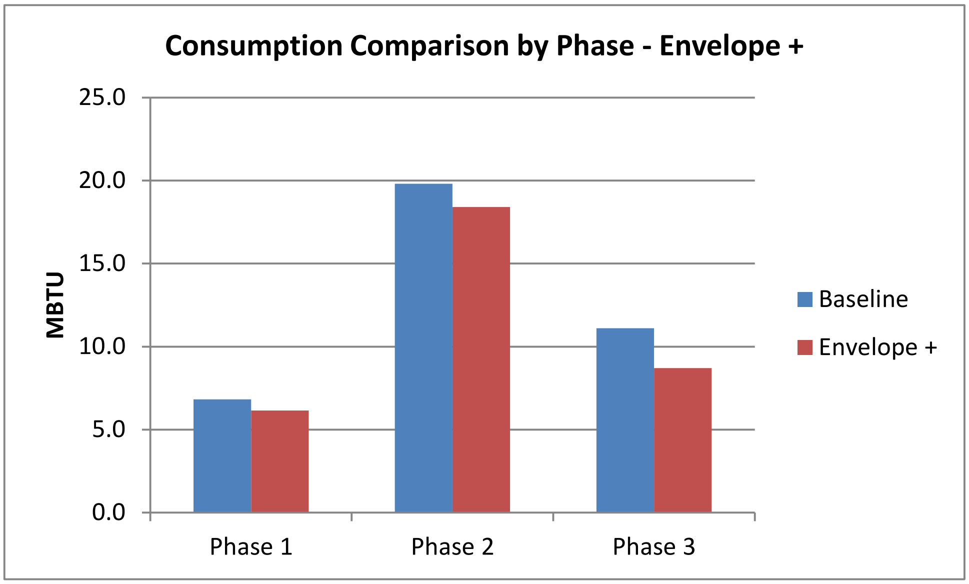

Fig 25. Comparison of energy consumption of retrofit scenario "Envelope +" and baseline scenario by curing phase

5.2.3 Control Improvements

A second possible retrofit scenario that has been investigated is the installation of an automated ventilation control system that allows for following an exact curing schedule and thus preventing air to be ventilated before the acceptable humidity threshold has been reached.

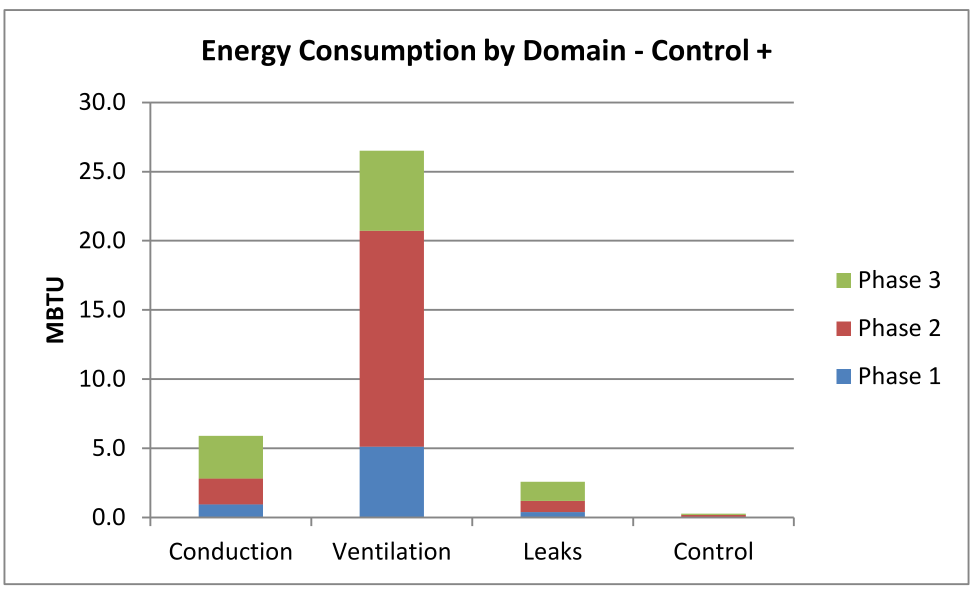

Fig 26. Total energy consumption after retrofit scenario "Control +" has been applied. Over-ventilation has been reduced to a minimum.

For this scenario we reduced the over-ventilation from 30% to 5%, which would be the result of a standard error to be expected from a high quality humidity control systems.

The results presented in Fig 27 visualize the energy reduction in the control consumption domain, which reduced the ventilation control losses by 83%. Overall this retrofit scenario presents a savings potential of around 6% compared to the assumed baseline conditions.

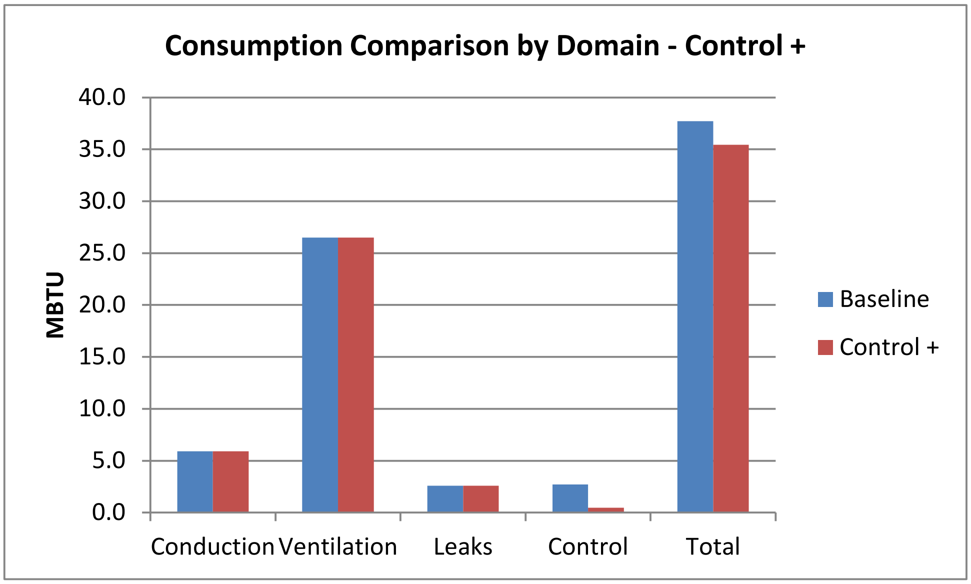

Fig 27. Comparison of energy consumption of retrofit scenario "Control +" and baseline scenario by consumption domain

Fig 28 shows that the main savings of this scenario are harvested during the second phase, the leaf-drying phase, in which about 60% of the total moisture is removed from the tobacco leaves.

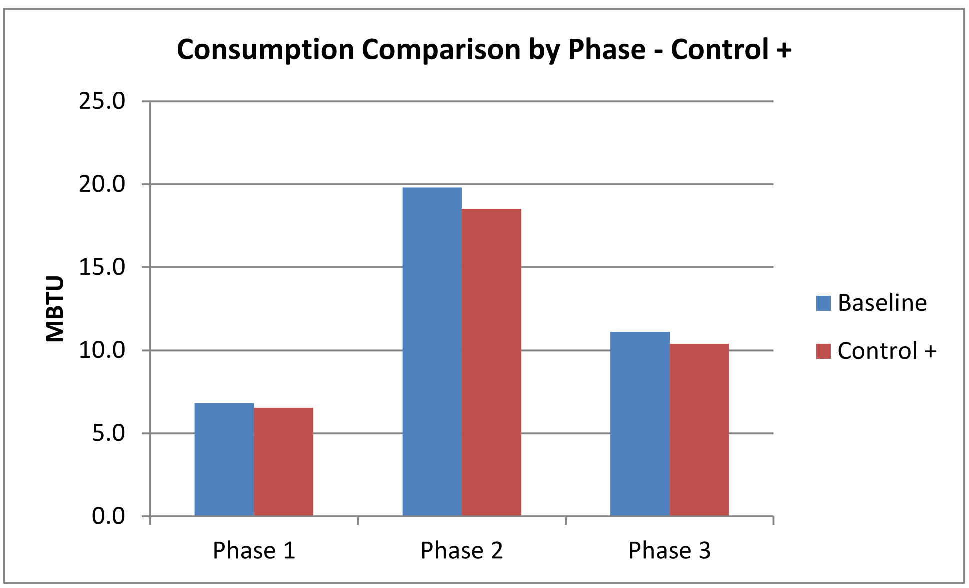

Fig 28. Comparison of energy consumption of retrofit scenario "Control +" and baseline scenario by curing phase

5.2.4 TOTAL RETROFIT

As a third theoretical modeling approach we combined the previous retrofit scenarios and at the same time further improved the envelope resistance. In particular we modeled the barn walls to be cladded with an additional 2" of continuous insulation boards that can be attached without creating significant thermal bridges. Furthermore, we introduced an improved, sub-terrain slab insulation similar to those found under shallow slab installations. These retrofit actions bring the roof and wall resistances to 11 and 12 $ft^2 \cdot °F/BTUh$, and also increase the thermal resistance of the floor to an estimated 5 $ft^2 \cdot °F/BTUh$.

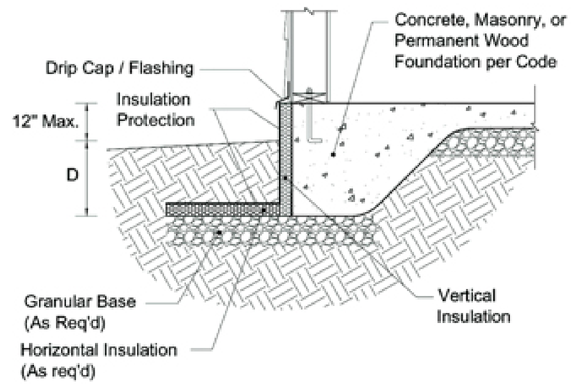

Fig 29. Introduction of a possible additional slab insulation for scenario evaluation purposes

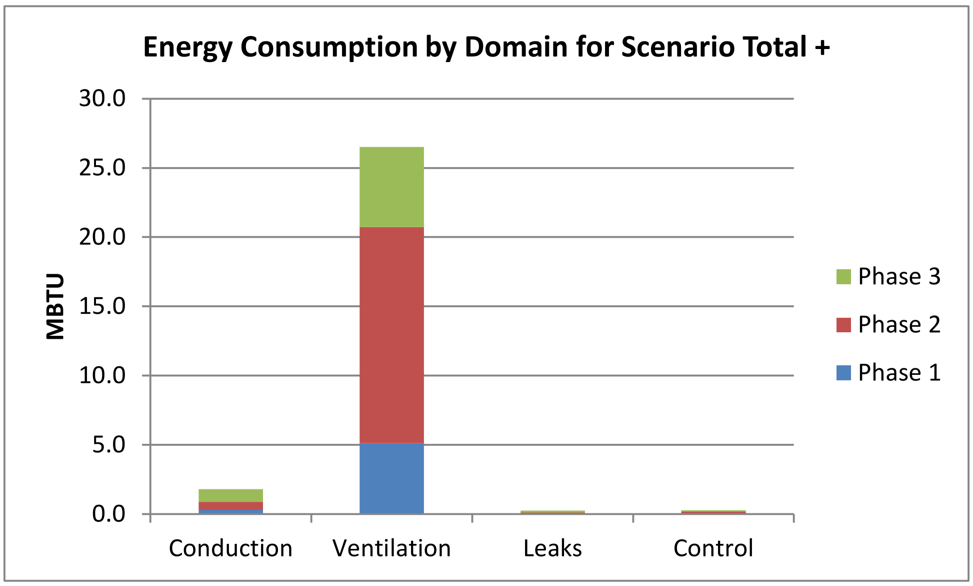

Fig 30. Total energy consumption after retrofit scenario "Control +" has been applied. Over-ventilation has been reduced to a minimum.

Fig 30 presents an overview of the significant energy reductions across all domains other than the ventilation domain.

In this scenario, where all other consumption domains have been addressed aggressively, the total consumption savings would come to around 25% of the total curing consumption. This seems to be a practical limit of savings against our baseline scenario without introducing special technologies for heat-recovery in the ventilation and dehumidification processes (compare Fig 31).

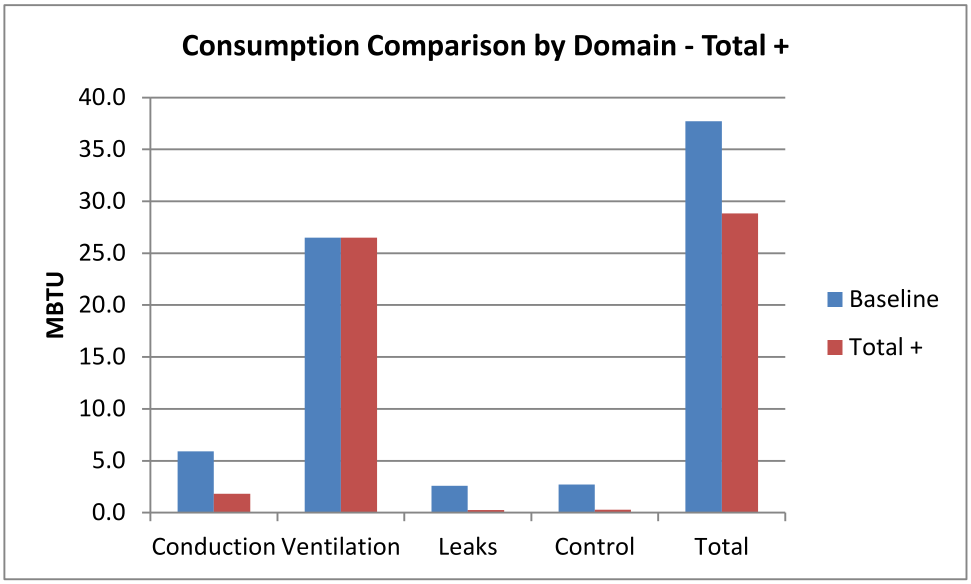

Fig 31. Comparison of energy consumption of retrofit scenario "Total +" and baseline scenario by consumption domain

Comparing the consumption across phases (Fig 32) we can observe that both drying phases would significantly benefit from the discussed scenarios. Depending on labor cost for light earthwork required for the perimeter insulation, this scenario may actually warrant faster return on investments than the labor intense opening and refilling of all individual cavities with additional insulation material.

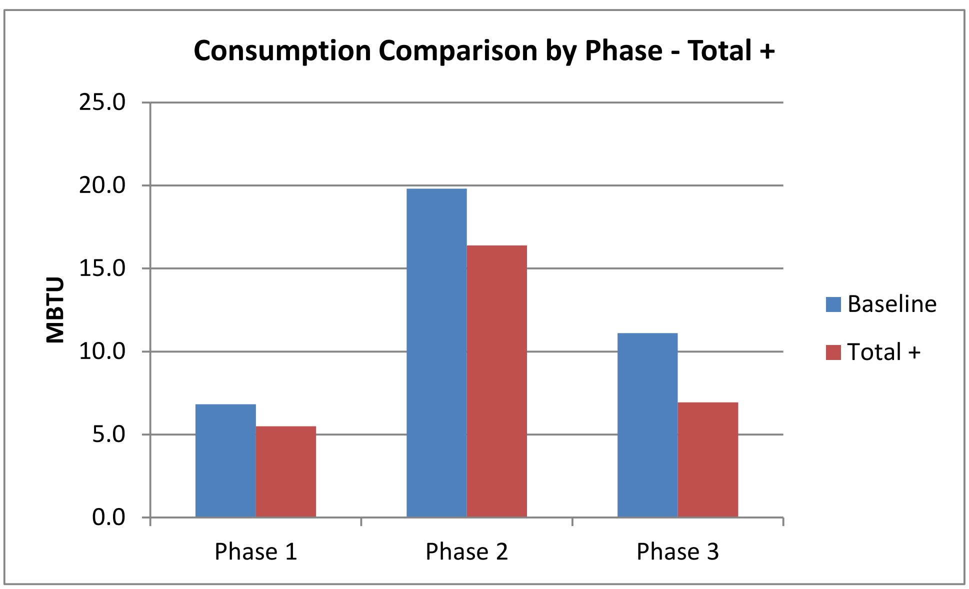

Fig 32. Comparison of energy consumption of retrofit scenario "Total +" and baseline scenario by curing phase

5.3 Impact of Environmental Boundary Conditions

To compare the impact of ambient environmental conditions as observed during different curing seasons, we investigated an additional scenario with typical environmental boundary conditions found in October. With significant colder night sky conditions the average temperature goes down into the higher fifties. For our assessment we still assumed an exterior temperature of 60°F and an average relative humidity of 75%.

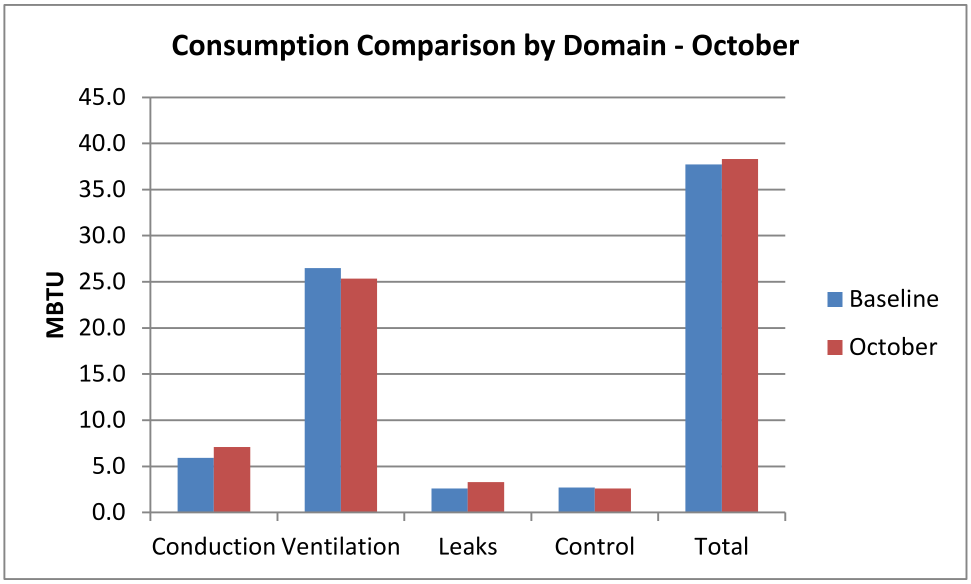

Fig 33. Differences of energy consumption of a curing scenario in October as compared to the baseline scenario under average August conditions

An interesting relationship now becomes apparent in Fig 33. While the total energy consumption in colder October climates will increase, the standard ventilation consumption decreases slightly. This difference can be traced back to the total ventilation requirements to control for relative humidity. Since the ambient October air is colder and less humid, it can absorb more vapor than the hotter and humid August air. While more latent energy is required to heat colder air to the interior set-point temperature, the total amount of exhausted air can be significantly reduced , which in turn makes the dehumidification process itself less energy consuming. Obviously, any retrofit scenarios that would attack the thermal conduction losses and infiltration leaks could yield higher savings during colder months than demonstrated in sections 5.2.2 to 5.2.4.

As shown by the results of this late season curing scenario, the exterior climate conditions have an impact on the curing consumption, though not as significant as someone would expect. Any return-on-investment algorithm should therefore provide for input of climate variances across a curing season to estimate the annual savings potential.

For validating this theoretical assessment model that has been developed within this project at a later stage it will be critical to clean for actual weather data on a daily basis during the observed curing cycles.

5.4 Alternative Retrofit Opportunities

5.4.1 Radiant Energy Harvesting Systems

Research conducted in the late seventies on thermal losses of curing barns concluded that radiant heat exchange in form of heat gains from the sun during the day and heat losses due to night-sky radiation compensate each other and are thus insignificant in the overall energy equations. While we concur that this is basically correct (compare Fig 34), this conclusion is based on the assumption that both sky conditions are exposed to the same envelope system.

If we now create a roof system that can absorb radiant energy during the day while shielding against cold sky radiation during nights we would create energy balances that could be used to our advantage. We believe that such a system is possible with today's technologies but would require experimental research for verification.

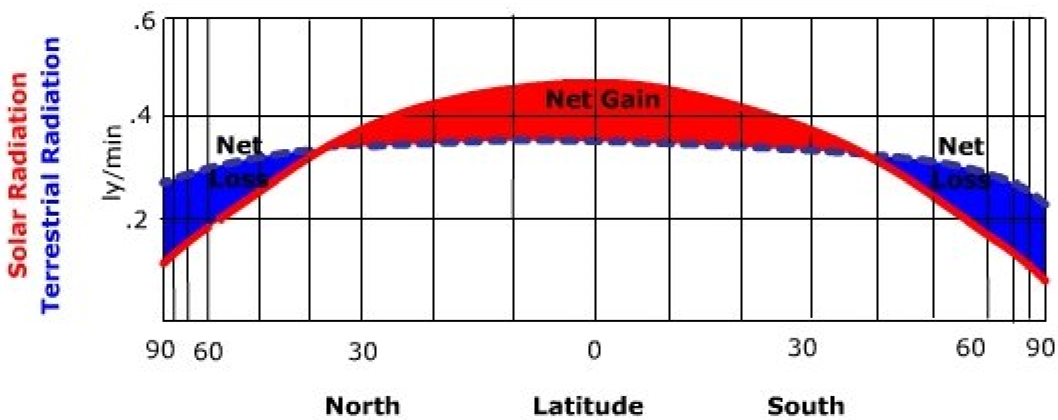

Fig 34. Variation in radiation balance by latitude – Danville, VA located on latitude 36.59°North

One such approach would be the investigation of coatings on nano-particle basis that possess different radiant exchange properties at different wave lengths. Such a coating could be easily applied to exterior surfaces and then investigated regarding effectiveness.

An alternative approach would be a cavity system that allows for radiant absorption of heat into the make-up air inlet stream that is utilized during the day, while it is routed differently during night times when this cavity would then be converted into an additional insulation buffer. This approach would require some technical (control) equipment, but could be easily developed and investigated in lab settings before tested in the field.

5.4.2 Psychrometric Heat recovery systems

As outlined in the model development section, evaporation is a heat energy absorbing process, which typically cools its surroundings when vapor gets "stored" into the air. To remain on a constant temperature level, sensible heat needs to be added to make up for these heat losses.

Exhausted air from the curing compartment typically holds a high level of latent energy that ultimately will condense somewhere outside the barn.

For example, interior air at 100°F and 83% RH has a dew point temperature of 93°F. Interior air at 165°F and 15% RH has the same dew point. In other words, whenever this air hits an environment colder than 93°F condensation will occur. This condensing process now releases some of the stored latent heat again as sensible heat, which ultimately creates a heat gain in its surroundings. What if we force this condensation to happen within our barn system? As long as we care for the developing condensate not to re-enter our air stream and curing compartment but rather drain it to the exterior, we could utilize the phase change heat gains from the condensing process to pre-heat our make-up air.

What if we force increased condensation along special placed "cooling ribs"? We can then re-use the less humid air after some condensate has fallen out, and consequently cut down on the required total air exchange rates to remove moisture, and thus further reduce the latent heat requirements that otherwise need to be provided by the furnace.

Again, these psychrometric heat recovery systems would yet need to be developed for scaled models that can be tested and evaluated in lab scenarios regarding feasibility and efficiency before being deployed and tested in the field.

Fig 35. Forced condensation for dehumidification at an evaporator coil within an air conditioning unit

6. CONCLUSION

This project successfully developed a theoretical assessment model for investigating the savings potential of retrofit scenarios for curing barns.

Within this project we evaluated only the most practical and also typical retrofit scenarios, such as envelope improvements and the installation of an automated control system. In terms of their anticipated impact on energy savings the different opportunities ranged from around 6% for added control strategies to around 12% for typical standard envelope improvements. A total upper limit of savings around 25% has been established, if more aggressive envelope improvements are paired with automated control systems. Obviously, these results can vary significantly depending on the baseline scenario. Without better knowledge and actual test data hand, we assumed for this project a poorly insulated, moderate leaky barn, with an experienced and careful grower manually monitoring the wet-bulb temperatures in the curing compartment.

While the commonly known retrofit scenarios tackle all consumption domains other than the dehumidification/ventilation domain, it became apparent that the most promising savings may lay in recovering some of the ventilation losses that are a result of controlling for the relative humidity in the curing compartment of the barn. We have to acknowledge that moisture evaporation is an energy consuming process. Nevertheless, it would be possible to recover some of the ventilated losses through radiant and psychrometric heat exchange processes.

The next steps of this program should expand the here developed model with associated cost data for regional growers. Return of investment assessments should be packaged as separate do-it-yourself versus contractor options to make them more attractive to versatile growers.

Besides establishing ROI tables, we believe that it would be worth investigating the savings potential of new, yet to be developed, energy harvesting and heat recovery scenarios for ventilation savings and evaluate them in scaled model experiments in laboratory settings.

7. References

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