Evaluation of Methods to Control Mold on Hardwood Pallets

Thomas R. Blount

Thesis submitted to the faculty of the Virginia
Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Masters of Science
in
Forest Products

Brian Bond, Chair
Marshall White
Henry Quesada

August 27, 2009
Blacksburg, Va

Keywords: Wood, Pallets, Mold, Air Drying, Kiln Drying, Fan Shed, Chemical Dipping, Heat Treatment.

Evaluation of Methods to Control Mold on Hardwood Pallets

Thomas R. Blount

(ABSTRACT)

The objectives of this project were:

1. To compare the drying cost and drying time for oak and poplar pallets for the following mold mitigation strategies for hardwood pallets: air drying, forced air drying (fan shed), kiln drying to 25% moisture content and chemical treatment, and
2. Develop and evaluate a procedure for preventing and controlling mold growth on heat treated hardwood pallets

Twenty red oak pallets and twenty yellow-poplar pallets were tested for each drying method to compare costs and to determine drying times. Additional pallets were obtained to conduct a more thorough air drying procedure. Drying data was extrapolated to allow estimates of the drying time from green (83% moisture content for poplar and 64% moisture content for oak) to 25%.

After the pallets reached the desired 25% moisture content, they were placed in a 40' enclosed trailer, inoculated with mold (Aspergillus, Stachybotrys, and Penicillium) and were left undisturbed for a period of 14 days. After the 14 day incubation period, the pallets were inspected for mold using the ASTM D-4445 Standard Test Method for Fungicides for Controlling Sapstain and Mold on Unseasoned Lumber.

A comparison of drying costs was then conducted to determine which method was the most cost efficient based on the data obtained in this study. The cost to treat the pallets with each treatment was calculated including electrical cost, labor, and tax values. In addition to the cost comparison, a Net Present Value (NPV) was calculated to determine which method produced the best outcome over a longer period of time.

Two heat treatment and drying schedules were then developed to meet both IPPC-ISPM #15 requirements and achieve the desired 25% moisture content with minimal degrade. This was accomplished by testing several HT/drying schedules on green yellow-poplar and white oak pallets until the pallets met the criteria for being heat treated and had minimal degrade. The schedules developed are a modified oak HT/KD schedule that required 30 hours to complete and a modified poplar HT/KD schedule that required 16 hours to complete.

The results demonstrated that that mold would not grow on the pallets stored in an enclosed container when the dew point is not reached. Air-drying pallets, chemical application in conjunction with air-drying pallets, fan shed drying pallets and kiln drying pallets to a 19-24% moisture content was demonstrated to prevent mold growth on oak and yellow poplar pallets. Estimates for the time required to dry yellow-poplar and oak pallets to 19% and 25% moisture content were developed for air-drying, forced air-drying and kiln drying for the conditions experienced in Blacksburg, VA between 7/30/2008 and 11/10/2008. Air-drying pallets was found to have the lowest daily operational cost but not the lowest total drying cost. Fan shed drying had the lowest drying cost to achieve 25% moisture content. Kiln drying was the most expensive daily and total cost, but yielded the fastest method of drying pallets to 25% moisture content. A NPV cost comparison showed that over a 3 year (36 month) time period, fan shed drying is the most cost effective method of drying pallets based on the values used in this study. Given the environmental conditions experienced between 7/30/2008 and 11/10/2008, no mold grew on the air-dried, fan shed, and kiln dried pallets during the drying process.

Table of Contents

Tables

Figures

Equations

Chapter 1: Introduction

A pallet is a portable, horizontal, rigid platform used as a base for assembling, storing, stacking, handling, and transporting shipping containers as a unit load (Twede and Selke, 2005). Pallets are vital for commerce since the majority of consumer goods that are transported; including foods, metals, paper and printing, and chemicals are moved on pallets. There are between 1.9 and 2.0 billion pallets in use each day (White, 2004). The wooden pallet and container industry is an important component of the wood industry since it uses large amounts of lumber. In 2006, 441 million new wooden pallets and 321 million repaired pallets were used in the United States. In 2006, 4.2 billion board feet of hardwood lumber was used in the United States for the production of pallets and wooden containers (Bush and Araman, 2008). Since the pallet industry is the second largest consumer of hardwood lumber; it is considered a vital market for low grade hardwood lumber and cants (Gaston et al, 2002). Wood makes up the vast majority of pallets because they are reusable, recyclable, repairable, and are made from a renewable resource.

Problem:

A major issue facing the wooden pallet and container industry is the potential for mold growth on the wood. According to U.S. Economic Research Service estimates, 96 billion lbs. of food are removed from the supply chain annually in the U.S. (27% of available food) (Browner & Glickman, 1999). Among the key reasons for this loss is spoilage caused by mold from pallets. Pallet customers are refusing new pallets that have mold growing on them for three reasons:

1) Mold can discolor and contaminate products, and

2) Mold can contaminate the workplace which can be a human health hazard, and

3) Mold pallets present bad visual aesthetics.

While pallets can be made from mold free materials, wood is more rigid and more durable than many of the other materials used for manufacturing pallets. Wood pallets are easily modified for customized needs, as well as readily available in extremely large quantities (NWPCA, 2007). Wooden pallets dominate the market because wood is relatively inexpensive compared to alternative materials (see Table 1), yet still has mechanical strength properties such as strength and stiffness that can exceed those of alternative materials. A significant advantage that wood has over other materials is that wood pallets can be repaired multiple times, unlike plastic pallets.

Table 1: Initial Pallet Price (2012)

Type	Initial Price (per 50)	Price (ea)
Plastic	$1,250.00	$25.00
Recycled Hardwood	$547.50	$11.00
New Hardwood	$850.00	$17.00
Pressed Wood	$575.00	$11.50

Source: www.epa.gov/wastes/conserve/tools/greenscapes/tools/pallets.pdf

While pallets are made from hardwoods and softwoods, hardwood use dominates the market with 74% (Bush and Araman, 2008). Hardwood pallets are made from a variety of commercial grade species including red oak (*quercus rubra*), white oak (*quercus alba*), and yellow-poplar (*liriodendron tulipifera).* Oak represents 22% and mixed hardwood represents 41% of the hardwoods used in pallet manufacturing (Bush and Araman, 2008). Pallets are typically manufactured from log cants which are the center of log that would produce low quality lumber; therefore, sawmills sell the cants to pallet mills who take the square cants and saw them into pallet parts. They are typically manufactured in the "green state", which typically is used to describe a moisture content[1] above fiber saturation point[2]. Pallets have typically not been dried

[1] **Moisture Content:** The amount of water contained in the wood, usually expressed as a percentage of the weight of the oven-dry wood.

because of the ease of manufacture when green and the end users generally have not required the pallets to be a specific moisture content. Since they are generally not dried, they can have significant problems with mold. Mold requires food, moisture, air, and warmth to survive. In the warmer seasons of the year, mold can be prevented by eliminating one of these 4 factors. Since wood could be poisoned with chemicals, and warmth cannot be eliminated, moisture is the most feasible factors to eliminate.

Mold on pallets presents the potential for contaminating goods that are placed on pallets, as well as introducing the mold into the surrounding environment. The food, agricultural, and the medical industry currently refuse pallets that have mold contamination. In the food industry, molds are considered to be detrimental to food quality (Williams, 2007). The agricultural industry ships feed, which could become contaminated, and potentially devastate the livestock herds. The medical industry does not want mold spores present on packaging of medical supplies, which could easily contaminate the supplies once opened (Williams, 2007). One specific example of the problem with mold on pallets in the medical field was a case from the contact lens solution manufacturer, Bausch and Lomb. In this case, mold was found to have contaminated the lens solution. People using the product were subsequently injured, and the product was recalled to prevent further injury. Although it was never determined where in the manufacturing process the mold contaminated the contact lens solution, the pharmaceutical company initiated an evaluation of the pallet manufacturer's mold control procedures to ensure their pallets were not causing the contamination (Bausch and Lomb, 2006).

Current strategies to combat mold on pallets are drying and chemical treatment. Drying pallets eliminates the moisture that is required for mold to grow. Drying the pallet as soon as

---

[2] **Fiber Saturation Point:** The stage in the drying or wetting of wood at which the cell walls are saturated and the cell cavities free from water. It applies to an individual cell or group of cells, not to whole boards. It is usually taken as approximately 30% moisture content, based on oven-dry weight.

possible reduces the risk of delivering a pallet contaminated with mold to the pallet user. Drying pallets can be achieved several ways. Kiln drying, air drying, and fan shed drying are three of the most common ways and will be considered in this study. The problem with drying pallets using these methods includes the additional cost of: a) running a dry kiln, b) space associated with air drying, and c) the electrical costs of running a fan shed. Chemical treating is another way to combat mold on pallets. The chemical biocides applied to the pallets act as a temporary barrier to prevent mold spores from germinating on the wood surfaces. The pallets (or pallet parts) are dipped into a chemical solution for a few minutes, then are allowed to dry. When dipping pallets in chemicals, they must still be dried to reduce the moisture content.

Due to the importance of the wood pallet industry on national commerce and the hardwood lumber industry, it is vital that cost effective mold prevention methods be provided to the industry. There is limited information regarding the time to dry and the cost associated with different mold prevention methods. By testing drying and chemical prevention methods for hardwood pallets under ideal mold growing conditions, this research will provide the industry with information they can use for comparison of time and cost for each of the treatments. Due to the variety of pallets and their uses, there may be no single "best way" to treat a pallet for mold, it all depends on the customer and their specific needs. This research will help the industry with a comparison of treatment methods so that they can select the method that best suits their needs and ultimately increase the wooden pallet industries competitiveness.

Objectives:

1. To compare the drying cost and drying time for oak and poplar pallets of the following mold mitigation strategies for hardwood pallets: air drying, forced air drying (fan shed), kiln drying to 25% moisture content, and chemical treatment, and

2. Develop and evaluate a procedure for preventing and controlling mold growth on heat treated hardwood pallets.

Expected Outcome:

The results of this study will allow manufacturers to choose the best method of mold prevention for their manufacturing environment and their customer needs. The prevention of mold on hardwood pallets is vital to assure that the industry does not lose market share to alternative materials.

Chapter 2: Literature Review

Pallets are an important market for the hardwood lumber industry. The pallet industry uses approximately 4.2 billion board feet of hardwood lumber a year in the United States (Bush and Aramam, 2008). The pallet industry is also crucial to the nations supply chain. There are approximately 2 billion pallets in use each day in the United States. In 2006, there were approximately 441 million new pallets and an additional 321 million pallets repaired and reused each year (Bush and Araman, 2008). Since pallets move all products, and provide a 25-30% demand for the hardwood lumber industry, it is important to continue using and improving methods to control mold.

2.1 Pallet

A pallet is a portable, horizontal rigid platform used as a base for assembling, storing, stacking, handling, and transporting containers as a unit load. Wood pallets are the highest volume category of solid wood packaging in use today. Pallets have openings in the ends to allow for a forklift to get under the top platform to lift the entire load. Pallets are used to transport goods all across the world. They are composed of runners that are perpendicular to the top and bottom deckboards which can be seen in Figure 1.

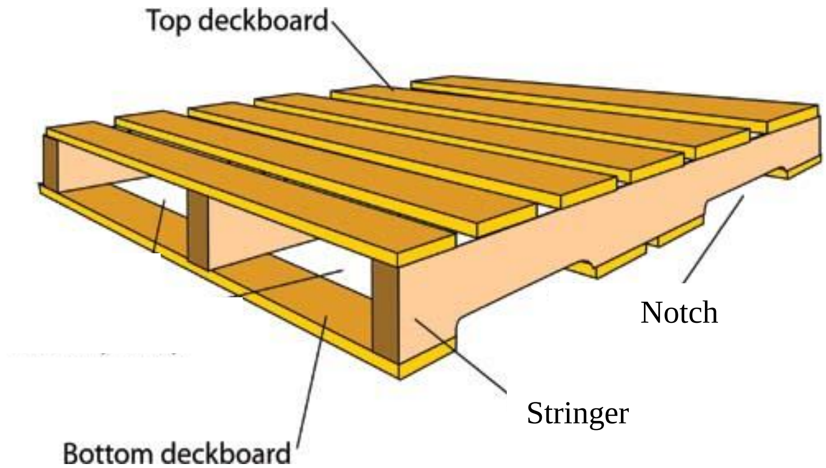

Figure 1: Stringer Pallet

Wood pallets can be broken down into two classes; stringer class and block class (Clarke, 2005). The first type is a stringer class, which is the most common type of pallet used in the United States (Clarke, 2005). Stringers are the continuous, solid-, or notched-beam components of the pallet that are used to support the deck. There are usually three, identified by their location as the outer or center stringers. The stringers are usually 2” x 4” in size. The stringers are what give the pallet its height, as well as rigidity.

The second type is a block pallet, which has blocks, instead of stringers, between the pallet decks. Blocks are rectangular, square or cylindrical deck spacers. A block pallet is always a four-way entry. Block pallets are stronger, yet more expensive to make than stringer pallets and are preferred by pallet rental companies because of their durability. Stringer pallets are generally less expensive to make because the process can be more easily automated (Twede and Selke, 2005).

The length of a pallet is determined by the length of the stringers, which is recognized as the first dimension given in describing a pallet. A 48” x 40” pallet has 48” stringers and 40” deckboards. Deckboards are the boards that run perpendicular to the stringers both on the top and bottom of the stringer. The height of the open end of the pallet needs to be sufficient to accommodate forks or pallet jack wheels, usually 3.75" (Twede and Selke, 2005).

Hardwood pallets are made from a variety of wood species including red oak (*quercus rubra)*, white oak (*quercus alba)*, and yellow-poplar (*liriodendron tulipifera)*. Oak represents 30% and yellow-poplar represents part of the 54.6% of the mixed hardwoods used in pallet manufacturing (Bush and Aramam, 2008). Pallet components are separated by wood species into classes (see Appendix A). Class 21 contains the eastern red (Quercus rubra) and white oaks (Quercus alba) species. Class 29 contains only yellow-poplar. The classes of species are ranked, according to relative strength and stiffness. This ranking system allows a quick estimation of which species of pallet components is stronger, or weaker, relative to your current species (Conway et al 2005). Hardwood deckboards provide more strength and stiffness relative to lower class hardwoods, to resist bending and breaking under the weight of the load. Some pallets have oak deckboards attached to softwood stringers.

Pallets are usually manufactured from green lumber or cants and in the pallet industry, a *green* pallet is considered having a moisture content greater than 25 percent. The ASTM D6199, *Standard Practice for Quality of Wood Members of Containers and Pallets* specifies that pallet members should have a moisture content at the time of fabrication no greater than 19 percent and no less than 9 percent of their dry weight basis (ASTM, 1999). However the MHIA/ANSI MH1 does not limit the moisture content of pallet components (Bush and Aramam, 2008). A moisture content between 9 and 19 percent would prevent many mold problems; however, this would be difficult to implement due to cost. Also, many pallet users do not require dry pallets, such as the automotive and tire industries.

2.2 Mold:

Molds are part of the fungi kingdom. Fungi are a diverse group of organisms within a wide range of species that include mushrooms, bracket fungi, molds and mildew (Robbins and Morrell, 2006). Fungi are small organisms that eat sugars and starches found in wood. The fungi produce an enzyme that enables them to digest the sugars and starches present in wood (Cassens, 1991). Mold is a type of fungus which can grow on any surface under the right conditions, which include food, suitable temperature (ideally between 70 and 85 degrees Fahrenheit), oxygen and moisture. Mold is very adaptable and can survive on any surface as long as these conditions apply, even glass surfaces (Robbins and Morrell, 2006).

2.2.1 Mold and Wood:

Conservatively there are more than 100,000 species of mold that exist in the world (Robbins and Morrell, 2006). There are over 1,000 species of mold that are common in the United States. Several hundred of the 1,000 or so species of mold attack wood products (Robbins and Morrell, 2006). The species that attack wood can be generalized into five groups of genera as described in Table 2.

Table 2: Mold Genera and characteristics

Genera	Location Found	Effects
Trichoderma	Soil, dead trees, paper	-Produces Antibotics that are toxic to humans -Readily degrades cellulose
Stachybotrys	Building material with high cellulose content and low Nitrogen content	-Produces a Mycotoxin which is harmful to humans
Fusarium	Plants and soil	-Can produce Mycotoxins
Penicillium	Grains, cellulose, soil, food	-Some species produce Mycotoxins
Aspergillus Versicolor	Hay, soil, wood products, cereals	-Allergenic Species -Can produce Mycotoxins
Chaetomium	Soil, air, plant debris	-Allergenic

Source: www.mold-help.org, 2009.

Trichoderma

Trichoderma can be harmful to humans, but is not as likely to cause harmful health effects as some of the other molds found on wood. Often, certain species of Trichoderma are used by blue jean manufacturers to produce a "stone washed" jean (Volk, 2004). Trichoderma, which readily degrades cellulose, is used to degrade the cellulose in the cotton, making a much softer fabric.

Stachybotrys:

Stachybotrys is a greenish black mold that grows on material with high cellulose content. This mold is a member of the Deuteromycetes, order Moniliales, family Dematiaceae (Lillard, 2004). It is commonly found in plant debris and soil and is one of many molds capable of producing one or more mycotoxins. Mycotoxins are chemicals that are produced by the molds that could cause symptoms or illnesses and death in people. The mycotoxin poisoning by this fungus is called stachybotryotoxicosis (Lillard, 2004).

Stachybotrys chartarum is found throughout the world and is typically wet and slimy to the touch. This species of stachybotrys is one mold type that requires ample amounts of moisture to get started, but after it gets established, it can still propagate after the source of water dries up.

People who have been exposed to toxins produced by this mold have reported cold/flu-like symptoms, memory loss, muscle aches, sore throats, diarrhea, headaches, fatigue, dermatitis, intermittent local hair loss, and generalized malaise (Lillard, 2004).

Fusarium:

Human Fusarium infection (Fusariosis) usually occurs in immunocompromised individuals, such as those affected by other diseases such as AIDS (HIV) or even a case of the common cold. Extreme exhaustion can also produce an immunocompromised state. Fusarium attacks cells in humans much the way it attacks cells in plants, through the secretion of mycotoxins that it itself is immune to. The mycotoxins produced by Fusarium dissolve the cell walls, and the fungus is then free to absorb the cell's contents, and enter the cell cavity, reproduce, and continue the process attacking other cells (Lillard, 2004).

Penicillium

Penicillium species are common contaminants on various substances which can cause food spoilage, and a sign of excessive moisture. Some of the Penicillium species are known to produce mycotoxins. The Penicillium species of mold commonly produces a strong musty odor. It is commonly found in soil, food, cellulose, grains, carpet, wall paper, and in organic substances (wood). This is one of the first molds to grow on water-damaged materials and has been known to cause allergic reactions, and a wide variety of severe lung complications (Lillard, 2004).

Aspergillus

The genus Aspergillus contains over 185 species, with 20 of the species known to cause harm in humans. Several of the species are known to cause harm in humans by infecting the lungs. Many people die from invasive Aspergillosis because there is no good diagnostic test. This infection usually attacks people with low immunity, often from major burns, AIDS, cancer treatments, and bone marrow transplants. This infection can sometimes transfer to the blood stream, spreading the infection to different parts of the body (Lillard, 2004).

Aflatoxicosis is another health illness that results from Aspergillus. This poisoning is caused by ingestion of aflatoxins in contaminated food or feed. This is often found in tree nuts, peanuts, and other oilseeds, including corn and cottonseed. This not only affects humans, it also affects livestock (Lillard, 2004).

Chaetomium

Chaetomium is commonly found on decaying wood products including water damaged drywall and often emits a musty odor. This mold produces spores which are very heat resistant, being able to survive 140 degrees F for 6 hours. Chaetomium can cause permanent DNA damage, being the only mold that inhibits cell replication. It is found in many substrates containing cellulose. The mold has the ability to dissolve cellulose and the process is especially rapid under moist conditions. Although this mold is not as common as some of the others, on a scale of worst to more mild in effects on human health, chaetomium would be second or possibly third to aspergillus only to stachybotrys (Lillard, 2004).

Several hundred species of mold attack wood products. Surface staining mold is one type of mold common in the wood industry. This mold produces fuzzy or powdery growths that can be many different colors. It is known as surface staining because the mold fungi do not penetrate below the wood surface. The surface of wood which has this type of mold can be easily sanded or machined to rid the appearance of the fuzzy growths. These type molds live where there is ample food, moisture, and warmth (Cassens 1991).

Sap staining fungi is one type of fungi that attacks logs and many wood products, mainly attacking the sapwood. This fungi stains the sapwood with dark colors of blue, black, and green. Sap stain penetrates deep into the lumber, so sanding or machining the lumber will not eliminate its unsightly appearance. Sap staining fungi increases the porosity of the lumber which allows for more water intake and provides a perfect location for decay fungi to invade. Where the sap stain is extremely heavy, there could be some minute decreases in toughness and its ability to withstand a shock load (Cassens 1991).

Mold grows on lumber from airborne spores that land on lumber with a relatively high moisture content (higher than 19%). Mold causes discoloration of wood, as well as some odor, depending on the type of mold. Mold does not degrade the wood properties; although it does increase the porosity which could lead to increased moisture content giving decay fungi a thriving environment to live.

2.2.2 Mold and Humans:

Mold enters the body by inhalation the mold “seeds”, called spores. These tiny spores can find their way through the respiratory system into the lungs, where they begin to grow. The spores are small enough to pass through the “filter system” that is present in the nasal passage. Those with severe mold allergies can reduce the risk of coming in contact with the mold spores by using HEPA filters, reducing the number of places where molds like to live, as well as regular cleaning (WebMD).

2.3 Mold and Wood Pallets:

Since the majority of wood pallets are manufactured in the green condition (MC > 30%), proper drying methods should be practiced in order to minimize the possibility of mold growth. Green pallets are usually shipped in closed trailers in the summer months, which can increase the temperature of the air and the pallets. As the trailer heats up, moisture escapes the pallets into the air in the trailer and the air becomes more saturated. In the evening as the temperature drops, the relative humidity may reach 100%, a point where no more moisture can be absorbed into the air. When this happens, liquid water forms on the pallet surfaces. During the day, this high relative humidity, along with high daytime temperatures provides a perfect environment for mold to thrive.

Wood pallets are relatively inexpensive to produce compared to alternative products, and it is important to be able to treat pallets in a way to stop mold growth inexpensively and effectively (see Table 1). By keeping wooden pallets relatively inexpensive, it will keep pallet users from switching to plastic or composite pallets, which are more expensive than wood pallets. Plastic pallets require more energy to produce, have a shorter lifespan than wood pallets. Plastic and composite plastics cannot be repaired as easily as wood pallets (Twede & Selke, 2005). There are several ways to treat a pallet for mold, each one will be discussed in detail in the next section.

As explained in section 2.2 there are health issues associated with mold contamination from moldy pallets both on the private consumer level and the large scale production level. Mold from pallets can contaminate agricultural feed, affecting the livestock that supplies much of the food to the US. Either the livestock can be harmed directly, or the mold can alter the structure of the meat that humans consume. The mold from pallets can also contaminate foods in transit to the grocery store. The mold does not have to come in direct contact with the actual food product. If the packaging of the food becomes contaminated, the consumer picks up the package, purchases it, then takes it home and prepares the food, their hands have become contaminated and in turn touched the food product that is being served. This indirect contact is enough to transport mold spores to the human body.

2.4 Mold Prevention and Treatments

Many different methods currently are used to prevent mold growth on wood products. These treatments can prevent mold for a certain period of time, but cannot prevent mold through the lifetime of the wood. After any of the treatment methods, if the wood becomes wet enough, with the right temperatures, mold will grow.

Sawn wood is more susceptible to mold problems, particularly in the green state due to such large surface area of green wood being exposed. Typical mold prevention methods include air drying, fan shed drying, kiln drying, and chemical treatments. These methods will be discussed in detail below.

2.4.1 Air-Dry

Sawn wood can be air dried alone, or used in conjunction with kiln drying to prevent mold growth. Stacking lumber with stickers between each layer and placing it on an air-dry yard is one way of drying the lumber to prevent mold growth. Also, placing the lumber on the air dry yard for a few days before going into the dry kiln can reduce the amount of moisture present in the wood when it goes into the kiln. Rapid drying of lumber, if possible will decrease or even stop mold growth on hardwood lumber. By removing the moisture out of the lumber, the chances for mold germination are minimized.

An air dry yard should be oriented in a way that the prevailing wind and the sun's path are optimized (Lamb). There are generally two layouts of air dry yards for lumber; the line yard and the row yard. The line yard (Figure 2) is oriented so the prevailing winds blow across the lumber stacks, for more control, or blowing down the alleys, for faster drying. The row yard (Figure 3) provides more control than a line yard because the spacing can be adjusted for a mix of wood species, with the easy-to-dry species on the outside rows. A line yard is easier to access, but a row yard gives more control of the air drying process (Lamb).

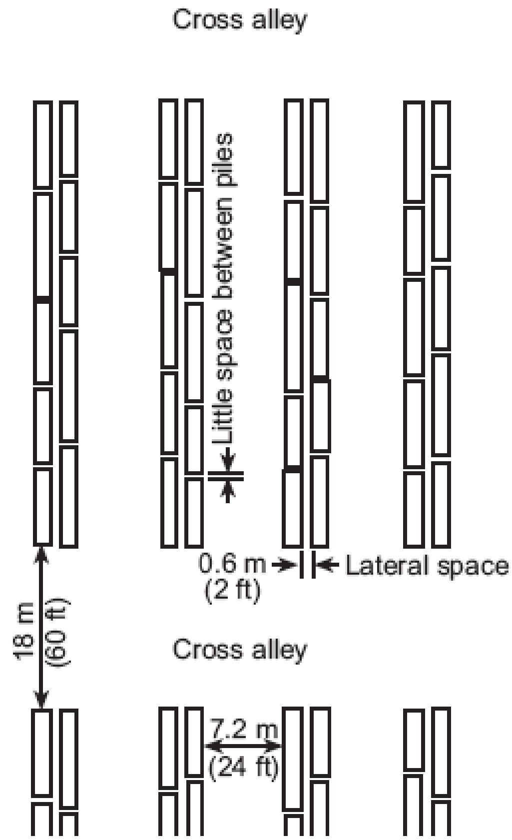

Figure 2: General appearance of a line type air dry yard (FPL, 1999).

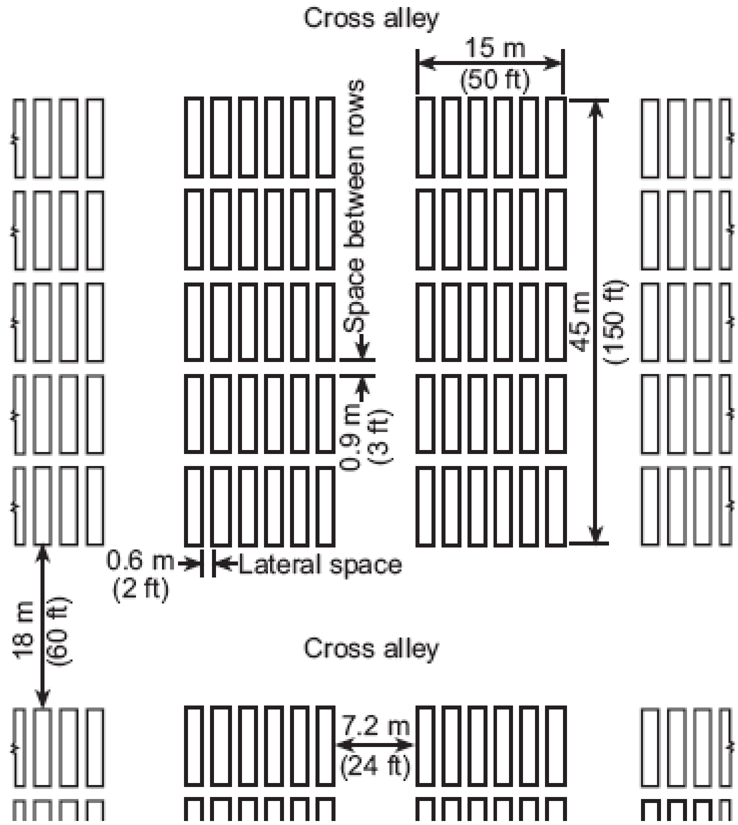

Figure 3: General appearance of a row type air dry yard (FPL, 1999).

Factors that Effect Air Drying:

Wood species and lumber thickness greatly affect air drying times. Thick lumber requires more drying time than thinner lumber when air dried. Some species of wood dry much faster than others. Wood grain patterns also influence the air drying times as flatsawn lumber dries much faster than quartersawn. Flawsawn lumber dries faster than quartersawn due to the orientation of the wood rays, which are a path for moisture movement from the core to the flat surface of the board. Also, the ratio of sapwood-to-heartwood has a great impact on the amount of air dying time. Sapwood has a higher initial moisture content, but it also dries at a faster rate than the heartwood due to the lack of extractive content (Simpson et al, 1999). The majority of the pallet stringers are made from log cants, making them almost 100% heartwood. The deckboards on the other hand, are typically made from slabs, which would be mostly sapwood.

The time of year, as well as wind speed, temperature, relative humidity, and amount of precipitation, affects the drying rate of hardwood pallets in an air-dry yard or a fan shed. Relative humidity has a greater impact than temperature on the drying rate on an air dry yard, as seen below. Table 3 shows the influence of relative humidity and temperature on the equilibrium moisture content. The Table shows that a changing temperature does not have as great of an effect on EMC as a change in relative humidity; thus average daily temperature is not as important as average daily relative humidity (Denig, 1980).

Table 3: Examples of the influences of relative humidity and temperature on the equilibrium moisture content.

Temp Constant 70°F			RH Constant 70 %	
Relative Humidity (%)	EMC (%)		Temp (°F)	EMC (%)
90	20.5		90	12.6
80	16.0		80	12.9
70	13.1		70	13.1
60	11.0		60	13.3
50	9.2		50	13.4
40	7.7		40	13.5

Source: Dry Kiln Operators Manual 1961.

Normally the drying rate doesn't change a great deal from week to week, but in some areas hot, dry winds can accelerate drying. A time period of increased relative humidity may delay the drying process. Rainfall greatly affects the air drying process not only because it increases the relative humidity, but it requires the excess moisture to be driven off (Simpson et al, 1999).

The floor system should be well drained, even if gravel is used as a base. Allowing all water to drain from around the packs, there will be no standing water around the lumber to increase the moisture content of the lumber. Weeds should be controlled to allow for proper air flow. Weeds and grasses between rows and stacks of lumber act as an obstacle for wind flow.

The area should be kept clean of broken boards, trash, and scraps of material used as stacking blocks to allow for constant flow of air through the facility (Johnson 2007).

Predicting Air Drying times of Wood:

Predicting air drying times of wood is no easy task due to the large number of variables that influence the process. Most attempts at trying to determine air drying times produced wide ranges of drying times, rather than precise numbers (Denig, 1980). Accurate predictions depend on the thickness of the lumber, the average daily temperature, average daily relative humidity, and the initial moisture content. Denig and Wengert developed a regression relationship formula for estimating daily moisture content (MC) loss (Denig and Wengert, 1982), based on testing 1" thick red oak and yellow-poplar lumber. The regression formula allowed the accurate estimate of drying times based on what time of year the lumber was placed on the air dry yard (Simpson and Wang 2004).

Equation 1: Daily Moisture Content Loss

$$\mathrm{DM} = a + b\mathrm{M}^{n} + c\mathrm{T} = d\mathrm{H}$$

Where:

DM = daily MC loss (%),
M = MC at the beginning of the day (%),
T = average daily temperature (F),
H = average daily relative humidity (RH),
a,*b*,*c*, and *d* = regression coefficients, and
n = 1 for yellow-poplar and 2 for red oak.
(Simpson and Wang 2004).

Advantages and Limitations of Air-Drying:

One advantage of air drying lumber or pallets to prevent mold is its low initial capital cost when compared to other drying processes, however, the air drying times required to prevent mold can be highly variable depending on the season and weather conditions. The rate of drying in the winter months is slow, yet the drying rate in the summer months is fast, increasing the risk for defects such as surface checking and end splitting. Also, the drying rate of lumber on the air dry yard depends on the changing weather conditions, such as temperature, relative humidity, precipitation, and wind (Simpson, Tschernitz, & Fuller, 1999). For example, while summer months typically have fast drying conditions, occasional long rains can completely alter drying rates thus making it difficult to accurately determine required inventories. Also, differences in drying rates will lead to higher inventories and require strong inventory management during slow drying times of the year.

2.4.2 Fan Shed

Fan sheds are a very simple way of drying wood by providing a constant air flow across the lumber. They consist of a roof to cover the lumber, and fans placed on one wall of the shed. The two side walls are solid with the front being open, allowing for additional air flow via air currents. Placing lumber into a fan shed will allow for a more consistent drying rate, as well as keep the lumber protected from rain, snow, and direct sunlight. If a fan shed is used, the drying time can be cut in half (White 1998). Drying times are reduced when lumber is first dried in a fan shed because as the air velocity increases, the drying rate increases. The fan sheds have a constant flow of air, providing consistent drying rates, which leads to minimal degrade (Denig et al, 2000).

When drying green or lumber with high moisture content, there is a considerable amount of water at and near the wood surface. The air flow across the lumber removes the water vapor and carries it away. The increase in air velocity yields a faster drying rate above fiber saturation point because the drying is dependent upon the air velocity. This relationship that air velocity and moisture content has on the drying rate above fiber saturation point can be seen in Figure 4. The more air that moves across the green lumber, the faster it will dry. Once the lumber reaches fiber saturation point, the air flow does not have as much effect on the drying rate as the temperature and relative humidity (Lamb, 2002).

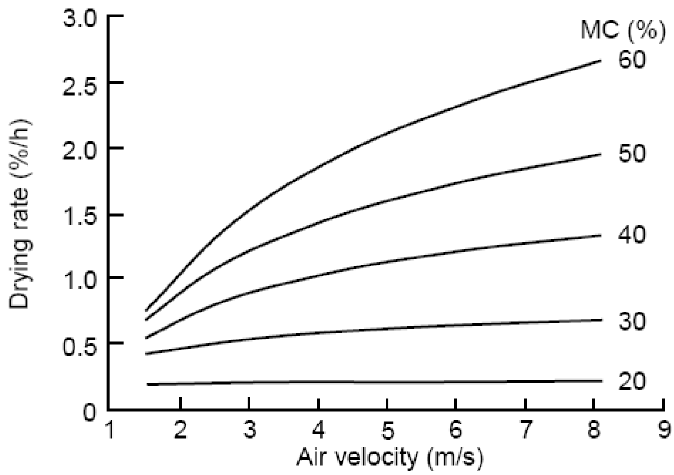

Figure 4: Effect of air velocity and moisture content on drying rate of sugar maple mixed sapwood and heartwood (Simpson, 1997).

Advantages and Limitations of Fan-Shed Drying:

Fan shed drying is similar to air-drying lumber, but there is more control of the drying rate. The shed's roof has adequate overhang which keeps rain and sun off the lumber, which increases the drying rate with little degrade. The rate of drying can be somewhat controlled by the fans by adjusting the fan speed. This adjustment in fan speed directly affects the drying rate by changing the air flow through the lumber. If the drying occurs too rapidly, the fans can be turned off to slow the rate of drying. Also, if the humidity approaches 90%, the fans can be turned off to eliminate the risk of re-wetting the lumber during a rainstorm or extremely humid days (Wengert, 2006). Where fan sheds have a more consistent air flow and are protected from precipitation more than an air dry yard, fan sheds have no control over the temperature and relative humidity in the shed. The temperature and relative humidity are the ambient outside conditions that may change hourly.

The cost of drying lumber in a fan shed is higher than the cost of air drying, mainly due to the electrical costs of running the fans, and also the cost of the shed itself. The cost of running the fans can be quite high, as well as the capital investment, which is fairly high in proportion to the amount of drying that can be accomplished (Nyle, 2009).

2.4.3 Kiln:

Kiln drying is different from fan shed drying in many ways. A dry kiln is a closed chamber in which heated, humidity controlled air is circulated through the packs of lumber as it is being dried unlike the fan shed, where temperature and humidity are dependent upon the weather. The temperature, humidity, and air velocity inside the kiln are controlled independently, depending on the species, thickness, and drying schedule. While kiln drying is the most consistent drying method to remove moisture out of wood, a dry kiln is only as efficient as the operator who runs it. It is the kiln operator's judgment to make changes to the kiln schedule based on the moisture measurements (Simpson, 1991).

Kiln drying requires several days to several weeks, depending on species, thickness and initial moisture content, to dry below 20% moisture content. This time can be decreased by placing lumber into a fan shed or air dry yard prior to kiln drying. The time in the dry kiln is decreased because the lumber has a much lower moisture content. The cost of operating a dry kiln is higher than the cost of placing the lumber into a fan shed or on the air dry yard because of the high initial capital cost of the kiln and all controls to effectively operate the kiln. A kiln requires fuel for heating the air and electricity to operate the fans. A fan shed requires energy to operate the fans, the capital cost of the shed itself, and the cost of the land; whereas the air drying requires very little costs, just the inventory costs and the cost of the land.

Advantages and Limitations of Kiln Drying:

Drying pallets in a kiln has many advantages, although the end result is the same as other drying methods: dry lumber to a specific moisture content while minimizing degrade. Dry kilns are able to closely maintain temperature and relative humidity settings, which produce more uniform and controlled drying. Kilns must be loaded, generally with a forklift, and must have a kiln operator to monitor the kiln conditions to be able to change the drying schedule as required. Since the majority of the dry kiln controls are electronically operated, one sensor malfunctioning or the boiler must be shut down, then the dry kiln can no longer be run. The generating of heat through direct fired, indirect fired, or a boiler can be expensive. The fans that circulate the air throughout the kiln require large amounts of electricity to operate, therefore further increasing the cost of running a kiln. Kilns are expensive to operate, but due to the minimal amount of degrade and the decreased drying times, the kilns can produce more consistent drying conditions than fan sheds.

2.4.4 Chemical:

The other method to prevent mold growth on wood is by treating the wood with a fungicide. Fungicides can be applied to wood by spraying or placing in a dip tank. The fungicide acts as a barrier that will last from three to six months. The fungicides are fairly mild and are not designed for long term durability (WWPA, 2002). Chemical treatments provide short-term protection by coating the surface of the lumber with a biocide chemical. To achieve the greatest effectiveness, biocide treatments should be applied immediately after sawing. In warm, moist environments the airborne spores of sapwood-stain fungi appear to germinate very soon after landing on the surface of the green lumber. The reasons for applying chemicals immediately after sawing is to ensure that a minimum amount of mold spores have made contact with the green lumber (Ward and Simpson, 1991). The earlier the chemical barrier is applied to the lumber, the greater your chances are of stopping mold growth.

There are many different types of biocides used today in the lumber industry. Below is a list of the common active ingredients in biocides (Johnson, 2007).

- Copper 8-Quinolinolate
- 3-lodo 2-propynyl butyl carbamate (IPBC)
- Chlorothalonil
- Methylele bis thiocyanate (MBT)
- TCMBT
- Didecyl dimethyl ammonium chloride (DDAC)
- Isothiazilone
- Propiconazole

(Johnson, 2007)

Advantages and Limitations of Chemical Treatments:

When chemicals are applied to lumber directly after sawing, it provides a temporary barrier that will prohibit mold contamination until the lumber can be kiln dried to reduce the moisture content below 20 percent. The biocide will not kill insect larvae feeding within the wood. It will also not control non-microbial enzymatic “gray” stain or mineral stain (Johnson 2007). Since the chemical treatment will usually not penetrate the lumber more than 1/32”, it is important to kiln dry the chemically treated boards at an initial dry-bulb temperature above 130 °F to prevent the core of the lumber from growing mold (Ward and Simpson, 1991). The chemical that penetrates no more than 1/32” of the board is not permanent. The fungicide can be diluted from moisture transfer through the board and will eventually wear off to the point where mold can survive.

Some users of pallets may not accept chemically dipped pallets due to possibilities of the fungicide contaminating their products. These industries may include, but are not limited to: Food and grocery industry and the pharmaceutical industry. These fungicides may react with foods or prescription drugs and cause unwanted contamination and spoilage.

Application Methods:

There are a number of ways in which pallets can be treated in order to reduce the possibility for mold growth. One way is to use an "across-the-chain" tank which allows individual boards to be passed through the solution via a chain that is suspended into the solution. A bulk dip tank can be used as well, where entire packs of lumber would be dipped into the solution. The lumber can also be sprayed with the biocide as the lumber passes through a spray booth (Johnson 2007). Pallets can be sprayed or dipped with a fungicide, much like the lumber process. Since pallets are generally much larger than pieces of lumber, it can be difficult to dip pallets, yet in a large dip tank, bundles of pallets can be dipped.

2.4.5 Heat Treatment:

Heat sterilization of lumber, timbers, and pallets is currently used to kill insects, preventing the transfer between countries in international trade. The IPPC is an international treaty to secure action to prevent the spread and introduction of pests and plants and plant products, and to promote appropriate measures for their control. Currently, the ISPM #15 requirement for heat treatment is holding a core temperature of 133°F for a minimum of 30 minutes (ISPM 2008). This time can be affected by species, specific gravity, moisture content, cross-sectional dimensions, initial temperature, heating temperature, type of heat (dry or steam), and the stacking method. ISPM #15 is standard application on all hardwoods and softwoods used in international trade. Heat sterilization is the most practical way to eliminate the transfer of insect infestations on international trade operations that use wood pallets and containers (Simpson 2005).

The treatments will kill the mold present on a pallet, but the pallet could be at risk of mold growth if the right conditions are met after treatment. Pallets that have been heat sterilized can gain moisture back, either from the air or direct contact with water. How the pallets are moved and stored after treatment can also influence mold growth. By having an increase in moisture content, mold could very easily grow on the wet wood. The obvious solution to the mold issue is to keep the pallets dry, but this is not an easy task when pallets are exposed to different environmental elements found in different parts of the world. High humidity could cause the pallets to gain enough moisture to be susceptible to mold growth. Elevated temperatures are also favorite mold living conditions. In many places, pallets may be exposed to the weather, either in storage or actual transportation paths.

Estimating Treatment Costs

Estimating the costs of a process is typically done using a cost accounting approach where costs are considered as either variable or fixed costs. Variable costs are those that change with a change in the amount of production and fixed costs are those that do not. The cost account approach has often been used to determine the costs of drying operations. One methodology that has been used for determining the cost of an air dry facility is described in the Agriculture Handbook No. 528 (McMillen, John M., and Wengert, Eugene M. 1978). The basis of the analysis can be seen in Appendix C.

When comparing different processes, it is often useful to not only know what the initial costs associated with the different operations are, but also what return on investment can be expected over time. A Net Present Value (NPV), also called Present Worth (PW), is a cost comparison where future costs and revenue estimates are transformed into equivalent dollars today. Initial cost, annual operating cost, and salvage values are used in determining the best viable method. This allows us to determine the best economical advantage of one method over another (Blank & Tarquin, 2005). NPV calculates "how much" money one method will produce over a period of several years. Initially, one method may have cheaper initial cost, but years later, the amount of return on the initial investment is null compared to a method which may have had a much higher initial cost. NPV takes what you have today and will tell you approximately how much it will make you in a certain number of years.

2.5 Overview:

Several methods for preventing mold growth on hardwood pallets can be used. While each of the methods prevents mold, not every method is feasible for each pallet user. Air drying pallets costs less, but the drying rates are very dependent upon the weather conditions, and there is no guarantee when the pallets will reach the target moisture content. Fan shed drying pallets is more consistent than air drying, but requires electrical costs of operating the fans, and the costs of building the sheds. Kilns are more expensive than fan sheds, but by controlling the drying conditions in the chamber, the lumber is dried at a desired rate and monitored closely to eliminate drying defects. While the kiln is more expensive, the lumber produced from it is of high quality and each kiln has a fast cycle time when compared to other drying methods. Chemical dipping lumber and pallets is the last method discussed in this chapter. Fungicidal dips prevent mold growth on lumber until it can be dried below 20% moisture content. The dips are a temporary way of preventing mold on lumber, but it is possible for mold to grow on chemically dipped wood after the fungicide wears off and the wood regains moisture.

With synthetic materials coming into the pallet industry, eliminating mold growth on hardwood pallets will keep the expensive alternatives from capturing market share. The synthetic pallets are more expensive and are not easily repaired, unlike hardwood pallets. When the synthetic pallets find their way into landfills, they will remain there much longer than wood pallets.

There is no comparison of the effectiveness of the different treatment methods for preventing mold on hardwood pallets. However, there has been some testing to determine how effective an individual treatment is at reducing mold growth, but none that compare the many different treatment types to each other, just the effectiveness of each individual treatment at different environments.

Determining the best treatment method for pallet manufacturers all depends on the types of customers who they supply. Pallets for grocery items may have more strict rules than pallets for automobile parts. Pallet manufacturers may not know which type of treatment best suits their needs; however, they probably would prefer the cheapest option, even though they may not know how it compares to other methods. This research will provide manufacturers with a comparison method, including the costs and effectiveness of each treatment. Net Present Value (NPV) calculations will allow manufacturers to see long term costs associated with each treatment method. By having this information available, pallet manufacturers may be able to switch treatment methods to better accommodate their needs.

Chapter 3: Methods

The goal of this research is to provide hardwood pallet manufacturers with a comparison of the costs and effectiveness of the most common mold prevention strategies for hardwood pallets. The information provided will allow manufacturers to choose the best option in the context of various manufacturing environments and customer requirements.

Objectives:

1. To compare the drying cost and drying time for oak and poplar pallets for the following mold mitigation strategies for hardwood pallets: air drying, forced air drying (fan shed), kiln drying to 25% moisture content and chemical treatment, and
2. Develop and evaluate a procedure for preventing and controlling mold growth on heat treated hardwood pallets

Testing was conducted on green yellow-poplar and oak pallets. Green pallets were dried to a moisture content of 25%. The time to reach the target moisture content was recorded in addition to climatic variables. Costs for each treatment method were estimated and used for comparison of each method. The costs incurred included labor, electricity, and initial capital investment. After the pallets were dried, they were exposed to mold spores and placed into a chamber exposed to the sun where the temperature and relative humidity changed as the external temperature changed, replicating conditions found in a closed container during the summer. The pallets were inspected and evaluated for mold growth after a period of 14 days.

This project was in two phases. The first phase included collecting data to evaluate and compare the cost and effectiveness of air drying, kiln drying, fan shed drying, and chemical treatments based on the treating time estimates of operating cost and the effectiveness of the treatment to prevent mold. All testing was conducted at the Brooks Forest Products Lab at

Virginia Tech. Chemical treatment supplies were obtained from a leading manufacturer of chemical treatment for wood pallets. The two fan sheds were constructed on campus for this project, as well as for future testing.

The second phase of this research was to develop a HT/kiln dry schedule that will both meet HT requirements and achieve the desired 25% moisture content with minimal degrade. This was accomplished by testing several HT/drying schedules on green yellow-poplar and mixed oak pallets until the pallets met the criteria for being heat treated and had minimal degrade.

3.1 Test Specimens:

Table 4: Distribution of pallets used in this study.

Number of Pallets Per treatment		
Treatment	**Oak Mix**	**Yellow-Poplar**
Fan Shed	20	20
Air Dry	40	40
Kiln Dry	40	40
Chem/Air Dry	20	20
HT/KD	40	40
TOTAL	160	160

Approximately 320 assembled hardwood pallets were used to evaluate the effectiveness of the fan shed, the HT/kiln dry method, traditional air drying, kiln drying, chemically treated, and the green control pallets as seen in Table 4. Half of these pallets were assembled out of red oak/white oak mix, and the other half were assembled out of yellow-poplar. Both species are commonly used in making pallets with oak representing 51% and yellow-poplar representing

11% of the total hardwood pallet industry (Twede and Selke, 2005). Oak represents a commonly used, dense hardwood that is difficult to dry and yellow-poplar represents a low high moisture content material. The pallets were picked up directly from the manufacturer immediately after manufacture. Testing began soon after arrival to ensure the pallets did not become contaminated and to start the test while the pallets still had relatively high moisture content.

3.2 Treatment Methods:

Each treatment was tested from 7/20/08 to 9/25/08 to represent the extreme cases of mold growth. The spring months typically have high humidity, but often high winds and cold night temperatures create conditions that greatly reduce the chance for mold growth. The fall months tend to have moderate temperatures with relatively low humidity levels. Summer months will typically have the highest temperatures and humidity as seen in Figures 2 and 3. Mold will grow at temperatures above 50°F, but the severity of mold is increased as the temperature and humidity increases. Table 5 shows that the wind during the summer here in Blacksburg is not as severe as the spring months; therefore, the summer winds will not excessively dry the pallets during the test. Since mold grows slowly in temperatures below 50°F, mold growth on pallets would be limited due to the temperature constraint; therefore, the idea of testing pallets for mold growth in the winter months was eliminated.

Table 5: Average wind speed and maximum wind gust for Roanoke, VA (NOAA, 1998)

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Average Speed	9	10	10	10	8	7	7	6	6	7	8	9
Max Gust	56	59	52	77	59	72	45	39	54	44	55	53

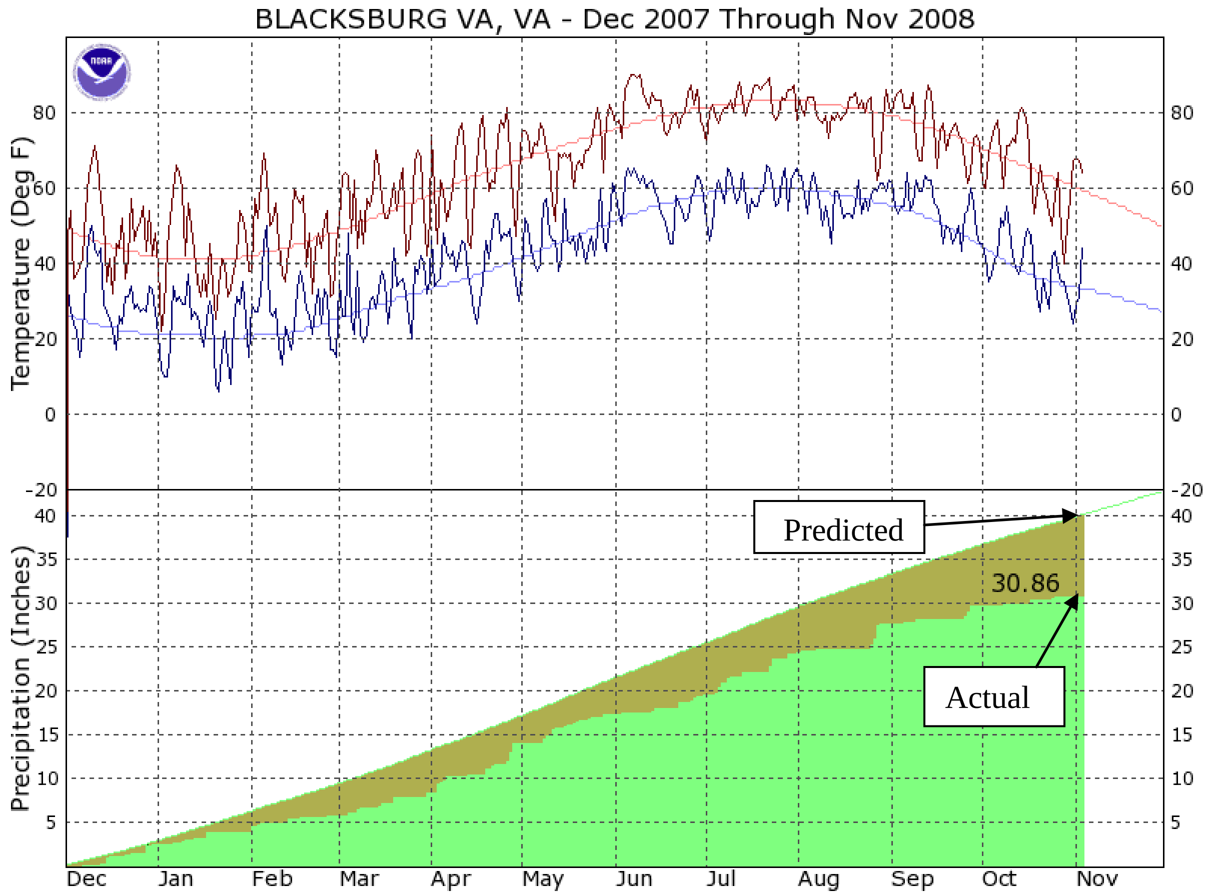

Figure 5: Monthly average temperatures and precipitation for Blacksburg, VA for December 2007 to November 2008 (NOAA, 2008).

Figure 5 above shows both the temperature and precipitation amounts from December 2007 to November 2008. The top part of the figure shows the high and the low temperature for each day, as well as the average high and average low temperature for the day. The bottom part of the figure shows the average precipitation for the year which is the smooth curve. The stair-step shaped green portion is the actual rainfall that fell between December 2007 and November 2008. The figure shows that expected rainfall amount for the year at November is 40", but the actual rainfall for the year was 30.86" of rainfall. Figure 6 shows how the average relative humidity changes with each change in month. This difference in average relative humidity values greatly affects the drying rate above fiber saturation point. September shows to have the highest average relative humidity, meaning that although high temperatures may be present, high relative humidity will slow the drying rate.

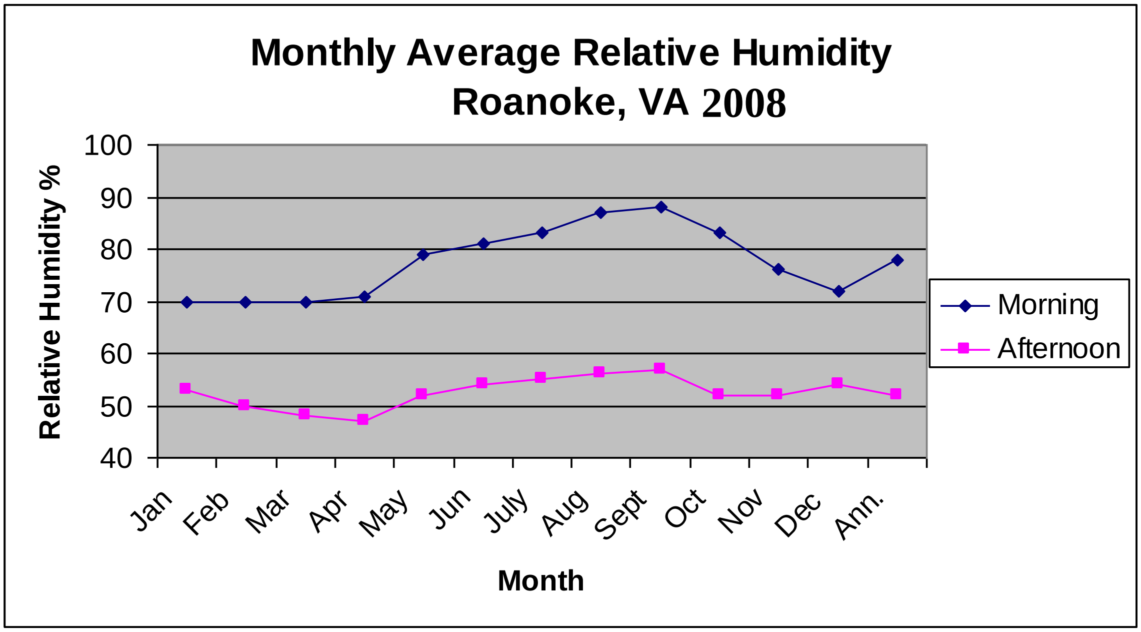

Figure 6: Average Monthly Relative Humidity Summary, Roanoke, VA (NOAA 2008)

3.2.1 Air Drying

Air drying data was collected and evaluated from 7/20/2008 to 8/30/2008 to approximate the drying time required to reach the target average 25% moisture content of the stringer component of the pallet. The samples used in determining this moisture content were pallet component parts, stringers, placed in the center of the area occupied by the pallets. These were extra stringers, full length, that were obtained from the pallet manufacturing facility. The stringers came from the same “lot” as the stringers used to manufacture the pallets. A total of 16 extra stringers were obtained, 8 oak and 8 yellow poplar, and were inserted into the center of the pallets to represent similar parts. Since these samples were full length, they were not end coated to allow them to dry at the same rate as the pallets.

Data recorded included average daily temperatures, average daily relative humidity, and wind speed. This data was collected because temperature, relative humidity, and wind speed have a direct affect on air drying lumber as explained in section 2.3. NOMAD OM-43 data loggers were used to collect the temperature and relative humidity and were set to take readings every two hours. The data loggers have ±1.5% accuracy on temperature and ±5% accuracy on relative humidity. Small wooden "houses" (see Figure 7) were made to keep the data loggers dry during the testing. Temperature, relative humidity, precipitation and wind speed was also collected from the National Weather Service for the Blacksburg area in conjunction with the data loggers (see Appendix B).

Figure 7: Data logger with protective shelter.

3.2.2 Fan Shed

Two fan sheds were built on site in order to have one shed for each species of wood (Figure 8). Since yellow-poplar and oak lumber dry at different rates, it was necessary to build two separate fan sheds to achieve optimal drying conditions for each species. The sheds each had two-36 inch Big Country Breeze Barrel Fans which pushed air at a rate of 400 feet per minute through the building from the back wall where the fans were mounted, through the pallets, and out the front of the shed. Yellow flagging tape was stapled to the pallets (Figure 8) to show wind movement through the stack as the fans circulated air.

Green hardwood pallets were force air-dried to determine the drying time required to reach the target average 25% moisture content. Average daily temperature and average daily relative humidity data was collected from data loggers as well as the National Weather Service for the Blacksburg area (Appendix B). The fan shed has a 5-V tin protective roof covering which eliminated the direct contact with falling precipitation; however, precipitation still increased the relative humidity during and right after the precipitation fell. The fans were turned 'off' whenever it started to rain and remained in the off position until the relative humidity decreased.

Figure 8: Fan sheds loaded with pallets.

3.3 Moisture Content Measurement

The moisture content of the pallet was taken by cutting a 10-inch sample from the center of the stringer as seen in Figure 9.

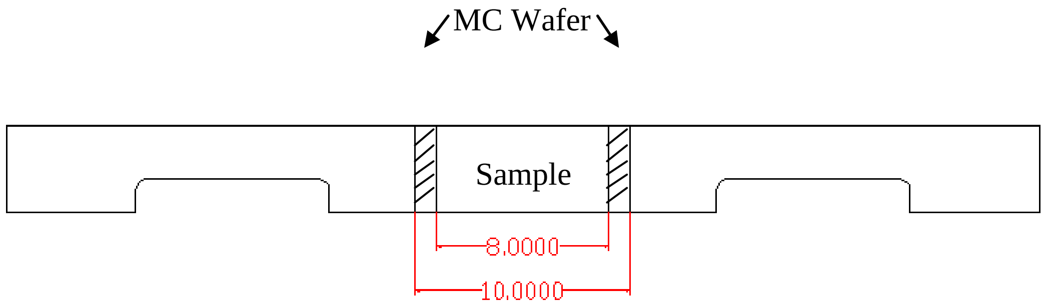

Figure 9: Pallet Stringer Moisture Content Section

One-inch wafers were cut from each end of the sample to determine the moisture content of the pallet at that time using the ovendry method (Equation 3). The moisture content was used to determine the "calculated oven dry weight" of the large sample. The "calculated oven dry weight" was calculated by Equation 2.

$$\frac{Origninal\ Weight}{100 + MC\ of\ wafers\ in\ \%} * 100 = Calculated\ OD\ Weight\ of\ Sample\ Board$$

Equation 2: Calculated Oven Dry Weight Equation.

The 8 inch samples were double end coated with an aerosol rubberized undercoating, then placed in the center of the pallets during the drying process. Each day the samples were weighed and the moisture content was calculated using that weight as the green weight, and the "calculated oven dry weight" as the oven dry weight in Equation 3.

$$\frac{Green\ Weight - Oven\ Dry\ Weight}{Oven\ Dry\ Weight}\ X\ 100 = MC\%$$

Equation 3: Oven Dry Moisture Content Calculation

3.3.1 Kiln Drying

This test was conducted to determine 1) the fastest drying schedule that resulted in the minimal amount of degrade and to base cost comparisons from the best schedule and 2) to determine the cost to kiln dry pallets using a moisture content based schedule. The moisture content data was collected from samples taken from the pallet stringers as discussed in section 3.3. The temperature and relative humidity that is used at each step in the drying schedule was recorded as well. Since there was some difficulty finding kiln schedules specifically for pallets, standard kiln schedules were used for each species as a starting point and will be discussed later in section 4.1.

The pallets were inspected both before and after drying for splits that would cause a pallet to be degraded. A split was counted if it was an open split (the split could be seen on both sides of the board) and only the splits that occurred in the connections were counted. The pallets were inspected before drying and all splits were marked with a permanent marker. After drying, if any new splits occurred, or existing splits got larger, it was easy to identify them. A pallet was considered a grade degrade if the split occurred through a fastener for at least 2/3 of the length of the member. Since the poplar schedule did not degrade any of the pallets, a more accelerated kiln schedule was used for the second kiln charge. The second kiln charge (Table 12) was more aggressive, yet still did not cause any pallet degrade.

After the first test, the pallets were evaluated to determine if the drying schedule was too conservative (no signs of harsh drying rates) or too advanced (extreme splits). If the schedule was too fast, a more conservative schedule was used to slow down the drying rate, which would decrease the number of pallets which were degraded due to the drying process. To make a schedule more conservative, the dry bulb temperature was lowered by 10 degrees while matching a wet bulb temperature that would give the same EMC as the original schedule. If the schedule showed absolutely no signs of drying stresses, a more advanced schedule was used to speed up the drying process. To make a schedule more aggressive, the dry bulb temperature was increased by 5 degrees with a depression that was slightly higher than the original schedule. These changes in the drying schedules were based on information provided from the Dry Kiln Operators Manual.

The T11-D4 schedule (Table 6) was used as a starting point for the yellow-poplar pallets since no pallet kiln drying schedule was obtainable. This schedule was used as a base schedule because the T11-D4 schedule is the schedule used for 5/4 yellow-poplar lumber. After the pallets were evaluated, changes to the schedule were made accordingly.

Table 6: T11-D4 Yellow-Poplar Kiln Schedule

T11-D4 Yellow-Poplar Kiln Schedule					
Step	% MC	Dry Bulb	Wet Bulb	Depression	EMC
1	Above 50	150	143	7	14.0
2	50 to 40	150	140	10	11.8
3	40 to 35	150	135	15	9.5
4	35 to 30	150	125	25	6.8
5	30 to 25	160	120	40	4.5
6	25 to 20	160	110	50	3.4
7	20 to 15	170	120	50	3.5
8	15 to final	180	130	50	3.5
Equalize	*	180	152	28	6.0
Condition	4 hours & cut test	180	170	10	11.1

The T4-C2 schedule (Table 7) was used as a starting point for the white oak pallets since no pallet kiln drying schedule was obtainable. This schedule was used as a base schedule because the T4-C2 schedule is the schedule used for 5/4 white oak lumber. After the pallets were evaluated, changes to the schedule were made accordingly if necessary.

Table 7: T4-C2 White Oak Kiln Schedule

T4-C2 White Oak 4/4, 5/4, 6/4					
Step	**% MC**	**Dry Bulb**	**Wet Bulb**	**Depression**	**EMC**
1	Above 40	110	106	4	17.6
2	40 to 35	110	105	5	16.3
3	35 to 30	110	102	8	13.6
4	30 to 25	120	106	14	9.9
5	25 to 20	130	100	30	5.7
6	20 to 15	140	90	50	2.9
7	15 to Final	180	130	50	3.5

3.3.2 Chemical Treatment

A biocide, as well as a brightener, was obtained from an industrial supplier of biocides, including the recommended concentration to use. This biocide is one that has been proven to control mold on wood products. The active ingredients in this biocide are Tetrachloroisophthalonitrile and Methylent Bis Thiocyanate. A 500 gallon agricultural tub was used as the dip tank. A 400 gallon solution was mixed in the container and was constantly circulated to ensure no settling of particles. A makeshift sling was fabricated to run through the bottom pallet and the ends were connected together above the top pallet. A forklift was used to lift the pallets and lower them into the solution. Pieces of steel were placed on the top pallet to ensure that the pallet did not float which would not allow for proper chemical saturation. The pallets remained in the chemical for a period of 2 minutes, then the pallets were lifted out of the chemical and all excess chemical was allowed to drain back into the dip tank.

The cost of chemical treatment of pallets for mold prevention was determined. This included the cost of the chemical and the time it took to treat the pallets.

3.4 Treatment Evaluation:

Once all the treatments had been completed, the pallets were placed into an air-tight container to ensure no contaminating airborne mold spores contact the pallets. To ensure all treatments receive the same conditions, all of the pallets were placed into the container at the same time. As the pallets were placed in the container, an aqueous solution with mold spore suspension was applied onto the pallets. The pallets remained in the enclosed environment for a period of 14 days to ensure enough time has passed for mold spores to germinate. A study conducted by Clausen and West (2005) revealed that specimens showed heavy mold growth after 7 days regardless of their original moisture content. Since the container will be air-tight, the only climatic factor affecting the pallets will be the change in temperature due to the rise and fall of the outside temperature. The pallets were left in the container undisturbed for 14 days to eliminate any disturbance in temperature and relative humidity inside container. Data loggers were placed in the containers during the 14 day cycle to record the temperature and relative humidity during the test.

Weather data was obtained from the National Weather Service Forecast Office in Blacksburg to keep track of the daily weather conditions, average daily temperature, average relative humidity, and average wind speed. These factors were recorded throughout the entirety of the testing. This information allowed us to conclude which treatment was most effective at these specific conditions. If the conditions were to change, seasonal change for instance, the results may vary. Relative humidity and wind speed are the two most important factors when drying wood. Data loggers were also placed at the testing site to ensure accurate daily data during the tests.

3.4.1 Air Dry:

The cost associated with air drying was determined by calculating the inventory cost to hold pallets at a facility for the length of time required to dry pallets from green to the desired 25% moisture content. Land values, as well as taxes were taken into consideration for making this cost analysis as accurate as possible. The methodology used for determining the cost of an air dry facility is described in the Agriculture Handbook No. 528 (McMillen, John M., and Wengert, Eugene M. 1978). The basis of the analysis can be seen in Appendix C and the formulas to calculate overall cost from the list are in Table 8. The numbers in parenthesis in the right column in the table below represent line numbers from the cost analysis methodology found in Appendix C.

Table 8: Air Dry Cost Formulas

Interest	[(21)*(13)]/12
Yard maintenance	[(29)+(30)+(31)+(32)]/(12)
Land interest	[(36)*(37)*(13)]/(12)
Taxes	[(42)*(48)]/(12)
Total insurance	[(47)*(49)]/(12)
Stacking cost	(50)*(51)
Forklift cost	(52)*(53)
energy cost	[(58)*(59)+(60)*(61)]/(12)
interest on inventory	[(62)*(64)*(13)]/(12)
degrade	(62)*(63)

3.4.2 Chemical

Since the chemically dipped pallets had to be air dried, the cost of chemically dipping pallets is the same as the cost of air drying, with addition to the cost of the chemical and the amount of time that was physically spent dipping the pallets. For this study, a labor rate of $10.00 per hour was used and the cost of equipment used to dip the pallets is included in the air drying cost analysis that can be seen in Appendix C in line 52 and 53. The cost of the chemical, as well as the cost to chemically dip pallets was obtained from the chemical manufacturer. The pallets were dipped while still green, and immediately placed onto the air dry yard. The chemical contained a biocide as well as a brightener.

3.4.3 Fan Shed

Fan sheds were constructed to test drying times and costs for forced air drying. The sheds were constructed in a way which will enable the shed to be mobile by means of forklift and a road tractor if needed. The fan sheds were fabricated so that it will hold more than 20 pallets because 20 pallets is the largest sample size that is feasible to work with on this project. Since two different species of wood will be dried, two fan sheds were constructed, enabling two different starting times.

The electrical energy cost was calculated by determining how many kWh were used in drying the pallets. This was done by knowing the wattage of the fans and the time period the fans are running. The equation for calculating this is: KWH = [(# of watts) x (run time in hours)] / 1000. The total number of kWh used was then multiplied by the electrical cost, which was provided by the Virginia Tech Electrical Service. The cost can be seen in Table 20 found in section 4.3. The cost of constructing the two fan sheds was approximately $750.00, which does not include labor. Labor was not calculated for actual constructing of the fan sheds.

3.4.4 Kiln Drying

The cost of each test was determined, and the amount of time required to reach the desired outcome of each treatment. The energy costs were estimated by determining the amount of BTU's per pound of water lost required to treat the pallets in the dry kiln, as well as calculating the heat losses associated with operating a dry kiln. A money figure was then placed on the amount of BTU's needed for a specific amount of moisture content drop. Figure 10 below shows how different moisture contents affect the differential heat of wetting and the latent heat of evaporation of bound water in wood at 150°F (Tschernitz 1991).

The heat loss from the dry kiln can be calculated using Equation 4:

Equation 4: Kiln Heat Loss

$$q = \sum U_i A_i (T_2 - T_1)_i$$

Where

q is heat loss through walls (Btu),
U_{i} overall heat transfer coefficient of individual dryer structural components (Btu/h/ft2/°F),
A_i surface area of walls, ceiling, floors, and doors (ft2),
t_2 dry-bulb temperature (°F),
t_1 exterior or ambient temperature (°F), and
Q_i drying time (h).

(Tschernitz, 1991).

Figure 10 below can be referenced when calculating the heat loss from the dry kiln during a drying schedule. This loss in BTU's must be accounted for when calculating cost because every BTU that is used must be paid for.

Moisture Content (%)	Differential heat of wetting (Δh_a) (Btu/lb)	Latent heat of evaporation (Btu/lb)[2]	
		λ'	β
20	27	1,034	1,034
15	55	1,062	1,048
10	113	1,120	1,072
8	151	1,158	1,094
6	203	1,210	1,117
4	270	1,277	1,144
2	360	1,367	1,175

[1]For moisture contents less than 20 percent

[2]λ = 1,007 Btu/lb H_2O at 150 °F

λ' = γ+ Δha Btu/lb H_2O removed at M_1

β = Btu/lb H_2O removed in the internal MC of 20 percent to M_1

Figure 10: Effect of moisture content on differential heat of wetting and latent heat loss of bound water at 150°F[1] (Tschernitz, 1991).

Venting losses in a dry kiln are the amount of energy lost due to opening and closing the vents to maintain proper temperature and relative humidity inside the chamber. Venting losses could account for up to 25 percent of the total fuel energy used in the dry kiln (Tschernitz, 1991). These venting losses were calculated using Equation 5:

Equation 5:Venting Losses

$$(t_2 - t_1)\left(\frac{0.241 + 0.492H_1}{H_2 - H_1}\right)$$

Where

T_1 = temperature outside the kiln
T_2 = temperature inside kiln
H_1 = Humidity outside the kiln
H_2 = Humidity inside the kiln.

(Tschernitz, 1991).

3.5 Heat Treatment of Pallets:

Green hardwood pallet material was heat treated to ISPM #15 guidelines and then kiln dried to an average moisture content below 25%. They were dried below 25% because mold can only survive in environments above 25%; reducing the moisture content, the risk of having mold growth is reduced. The heat treated pallets were not placed into the incubation trailer to be tested for mold growth. This part of the project allowed us to develop a heat treatment schedule that also dried pallets below 25% moisture content. The purpose for heat treating pallets is to sterilize the pallets from insects and their larvae to adhere to the wood pallet and container shipping requirements for pallets shipped to foreign countries. This requires that pallet material must be heated to 133°F for at least 30 minutes to eliminate any insects contained in the wood. Pallet degrade was measured and comparisons were made based on treatment time and pallet degrade. Pallet degrade consisted of measuring open splits both before and after the heat treatment.

Chapter 4: Results and Discussion

Since there are many factors in air drying and forced air drying wood, such as temperature, relative humidity, and air velocity, it should be noted that these results are for the specific conditions during each test and should be used as an estimate, and not exact figures. The kiln charges and heat treatment charges can be duplicated more easily than the air drying and the fan shed drying of the pallets.

The values are presented to give relative drying time and cost differences between the different mold control strategies. A methodology to determine more precise drying cost for an individual treater is presented. All results discussing pallet moisture content relate to the moisture content of the pallet stringer. Since the pallet stringers are thicker than the deckboards, the moisture content of the stringers is what was used to determine the moisture content of the pallet. If the stringers were dried down to 25% moisture content, the deckboards had already dried below 25%.

4.1 Treatment Methods

The air dry, chemical, and fan shed pallets were all dried under the conditions found in Figure 11. These values are averages from the NOAA reports for Blacksburg, VA 2008 that were compared to values obtained from the data loggers. There were only slight differences in the values which were disregarded. A total of 7.41 inches of rain fell between July 20 and September 27. The rain had a direct impact on the air dry yard due to the liquid water soaking into the pallets, rewetting them to a moisture content higher than when the rain initially started. The rain also had an impact on the fan shed pallets, but only due to the increase in relative humidity in the air. The fans were turned off during times with high humidity to try to eliminate any rewetting that could occur at times of high humidity.

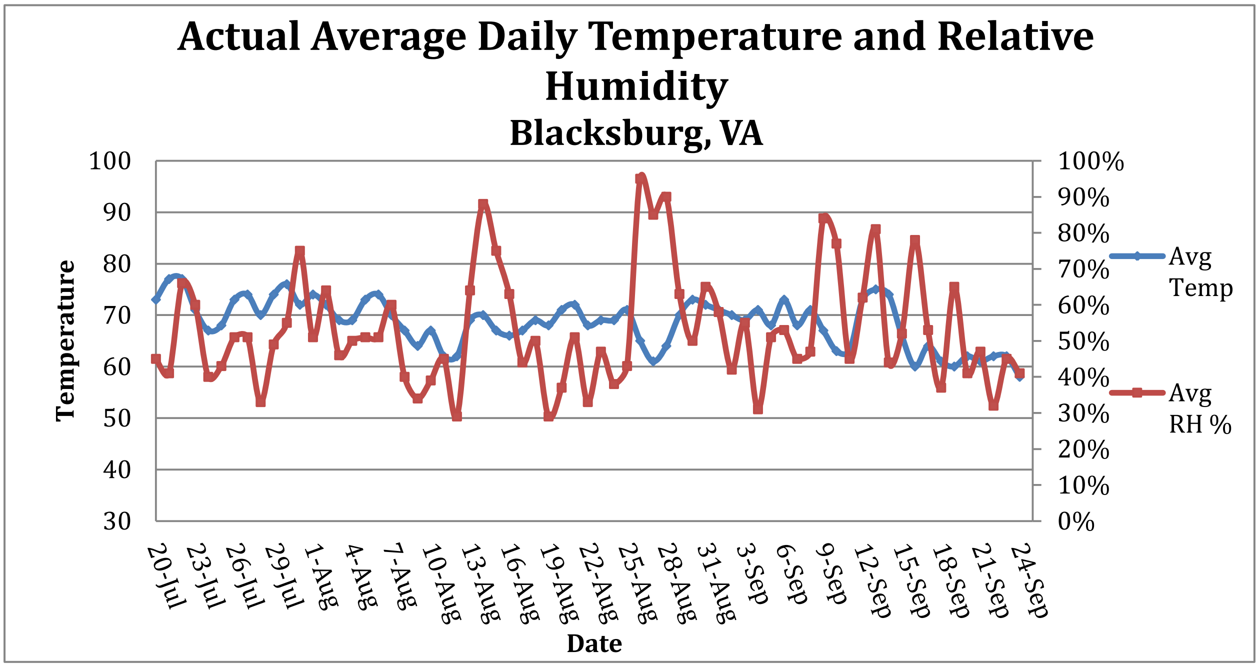

Figure 11: Actual Average Daily Temperature and Relative Humidity (NOAA 2009)

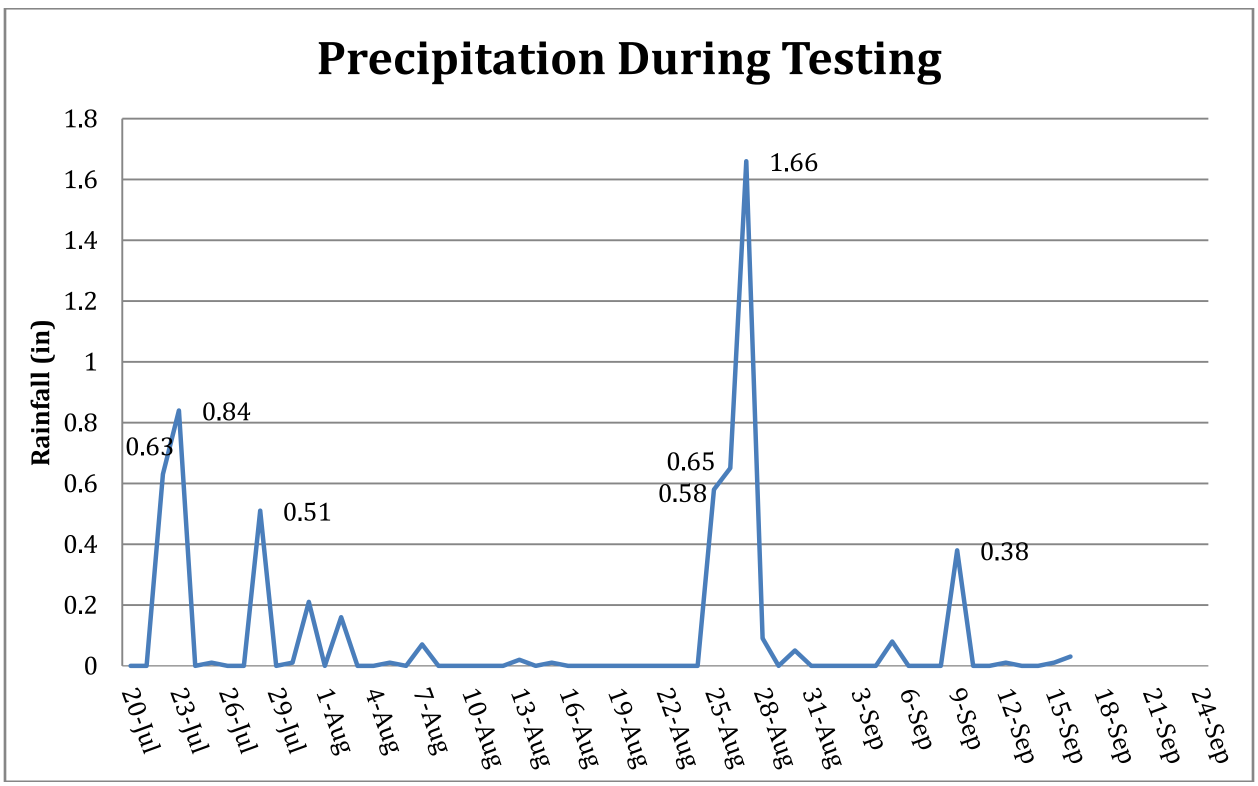

Figure 12: Actually Daily Precipitation (NOAA 2009)

The days of rain can be seen by the spike in relative humidity in Figure 11 and the corresponding daily rainfall amounts seen in Figure 12. The days with the most rainfall, August 25-27, had a total rainfall amount of 2.89 inches within that 3 day period. This amount of rainfall in such a short time period caused the air dried pallets to gain a significant amount of moisture, which caused longer drying times for those pallets.

4.1.1 Air Drying

The pallets that were air dried were placed on the air dry yard with the main openings of the pallets facing the prevailing winds that are typical for Blacksburg, VA. Wind speed was obtained from the National Weather Station located in Blacksburg, VA and can be seen in Figure 13. Ribbons were placed on the pallets to visually observe wind directions at any given time to ensure that the wind was blowing through the pallets. The pallets remained in the air dry yard and daily moisture content measurements were obtained from full length stringers until they reached 25% moisture content.

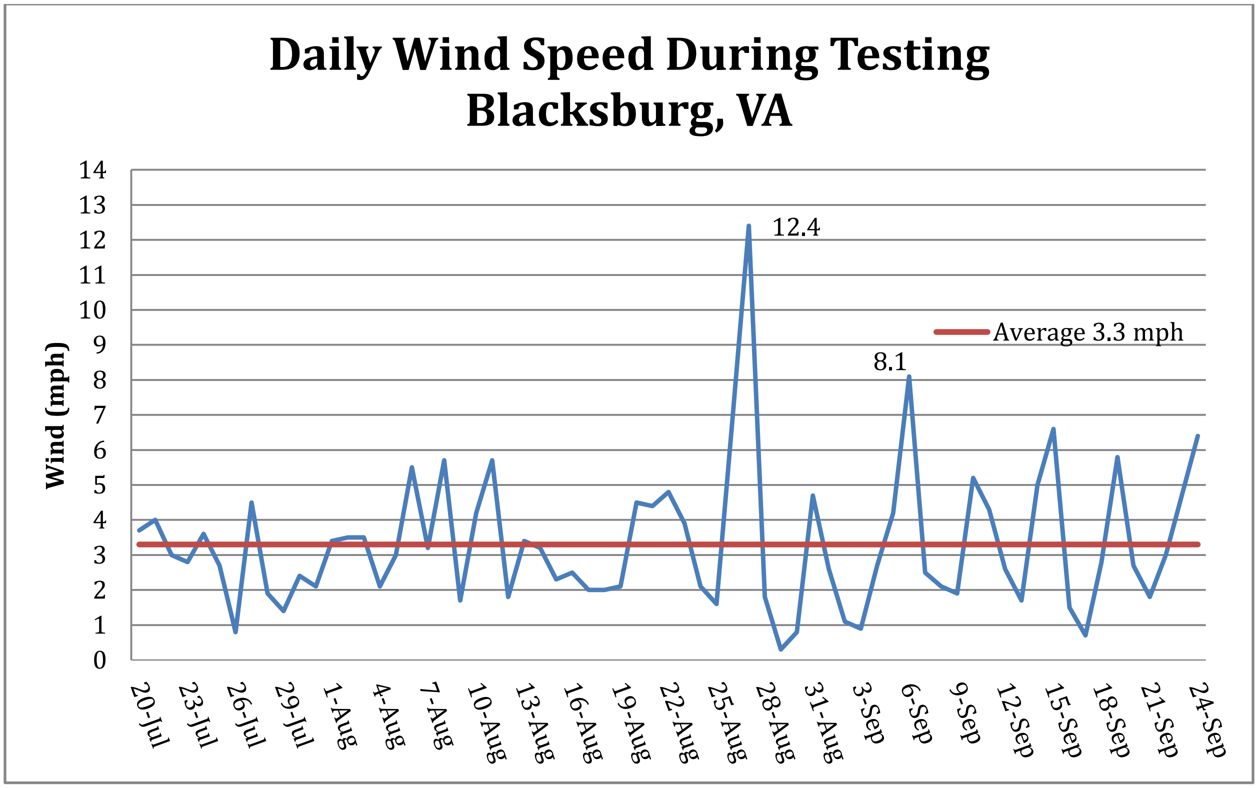

Figure 13: Actual Average Daily Wind Speeds (NOAA 2009)

Actual Air-Drying Times

The pallets that were used in this testing were made from log cants that were purchased from sawmills. Both the stringers and deckboards were sawn from sawmill cants that range anywhere from one week to two months old. The pallet facility from which all pallets for testing were procured operates its cant inventory on a first in, first out basis, but often times the fresher cants must be used to fulfill specific orders, depending on species. The cants that were used for the pallets tested had partially dried out, resulting in lower pallet moisture contents. The poplar stringers averaged 26.4% moisture content at arrival and the oak stringers averaged 38.8% moisture content. Although these moisture contents were lower than expected, they fell within the range produced by the manufacturers who provided pallets for this research. The initial moisture contents for the pallets used in this study are presented in Table 9. Since the pallets were procured over a period of time, thus representing different manufacturing dates, these values demonstrate that it is common for pallets to be manufactured green, but well below common freshly harvested moisture content values.

Table 9: Initial Moisture Contents of Pallets Before Testing.

	Poplar	Oak
Air Dry	26.4%	38.8
Extra Air Dry	57.7%	45.1%
Fan Shed	21.6%	36.9%
H/T 1	42.1%	55.6%
H/T 2	32.4%	49.2%
KD 1	33.1%	42.1%
KD 2	33.4%	44.3%
KD 3	39.1%	47.9%
AVG	**35.7%**	**45.0%**
Std Dev.	**11.0%**	**6.0%**
Low	**21.6%**	**36.9%**
High	**57.7%**	**55.6%**

Notice that the moisture content of the oak pallets is much higher than the moisture content of the poplar pallets. This is not what most would expect given the green moisture content for these species, but it can be explained. Initially, green yellow poplar lumber typically has a higher moisture content than green oak lumber. Typically green yellow poplar has a green moisture content of 83% heartwood and 106% sapwood and the oak typically has a green moisture content of 64% in the heartwood and 78% in the sapwood (Hoadley, 2000). Although poplar lumber typically has a higher moisture content than the oak, the poplar lumber can dry much faster due to the cell structure difference between the two species. The oak pallets in this testing yielding higher initial moisture content levels than the yellow poplar pallets, as explained above and can be seen in Figure 14.

Due to the low initial moisture content of the pallets, a second air-drying test was conducted from 9/29/2008 to 11/10/2008. The drying curves for this second test can be seen in Figure 15. The second air dry test that was conducted revealed slightly different drying rates.

This difference in the two tests shows how time of year has a great impact on the drying rate. Since test 2 has higher initial moisture contents, more of a curve is visible in the drying rates than the drying curve for test 1.

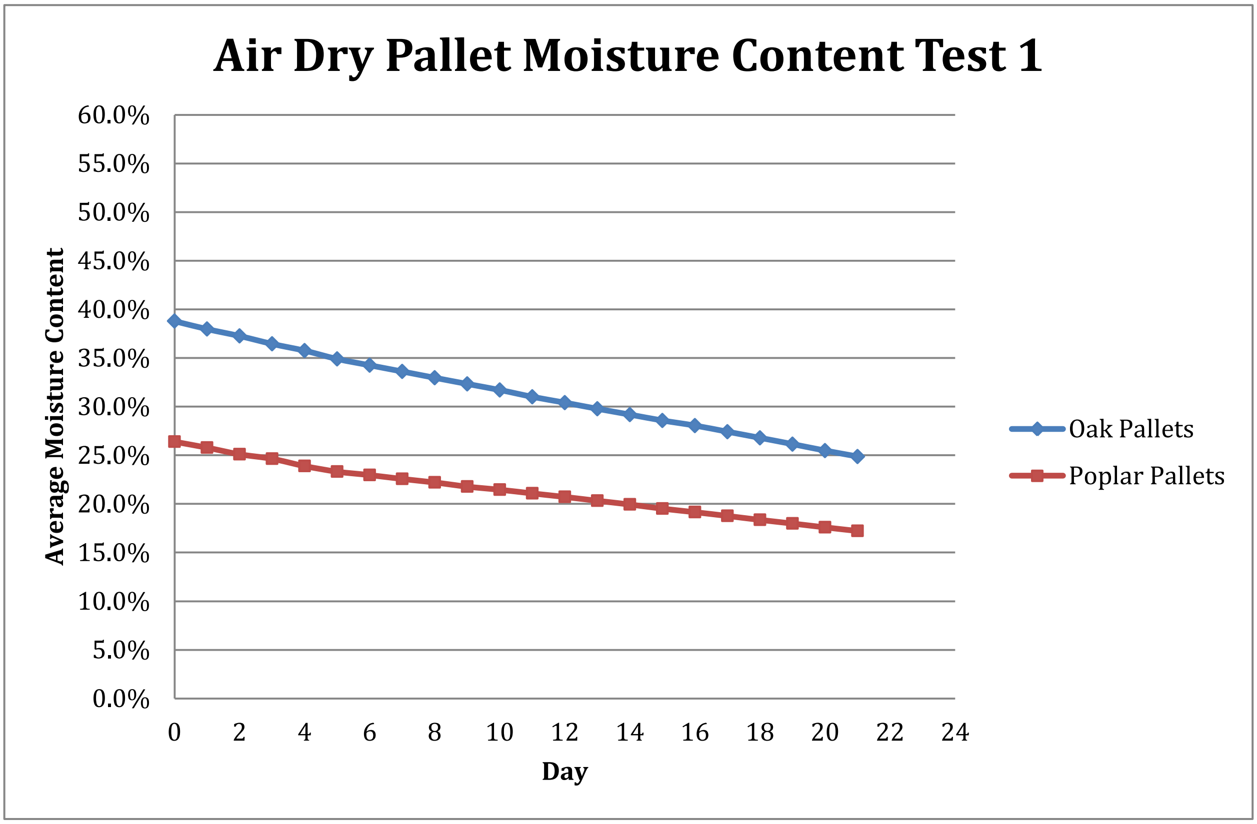

Figure 14: Actual Air Dry Moisture Content (7/30/08 – 8/25/08)

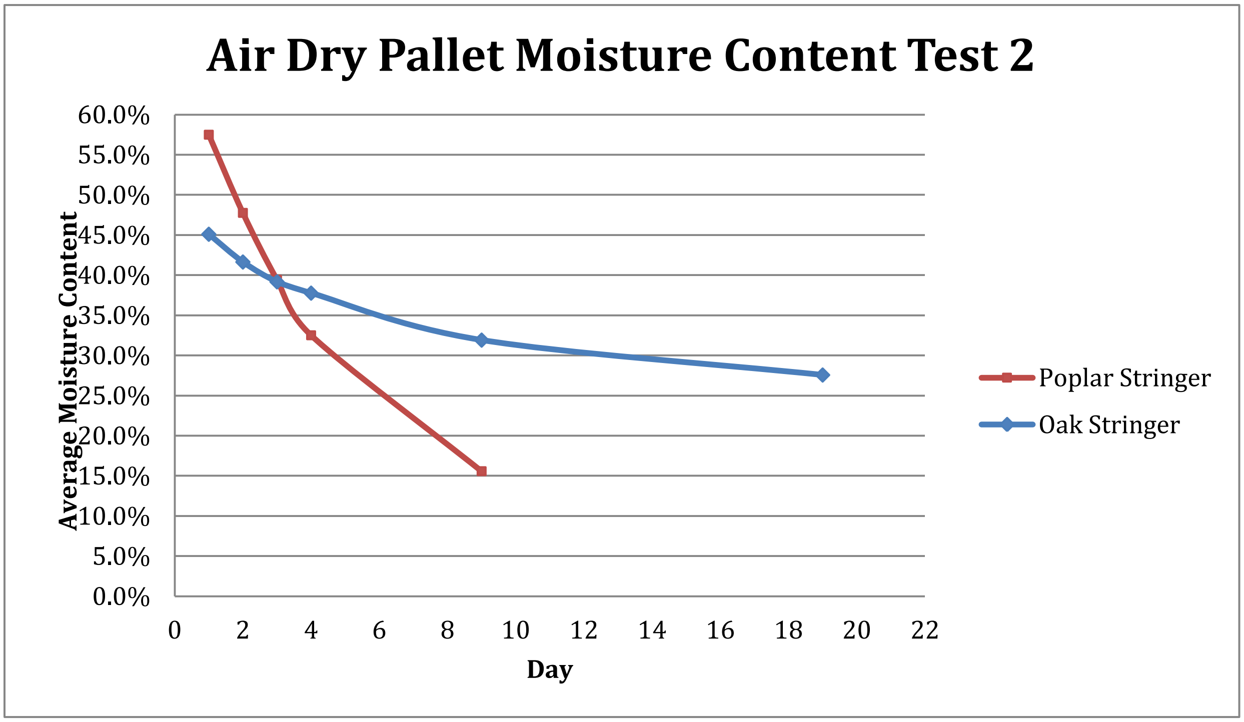

Figure 15: Actual Air Dry Moisture Content (9/29/08 - 11/10/08)

Extrapolated Drying Times

Pallet manufacturers make pallets from either logs that are sawn into lumber, or from log cants that are purchased from other sawmills, therefore, they may wish to determine drying times and costs using a different initial moisture content; therefore, the drying curves developed through experimentation were extrapolated to estimate the drying times required for pallets that would be made from freshly cut logs. Since the pallets in our testing came from cants and not directly from logs, the observed moisture content was lower than expected. Since pallet manufactures may produce pallets with higher moisture content, they need a method to estimate drying time and cost for higher moisture content material, therefore an extrapolation was conducted to determine the rates for higher moisture content material. Extrapolation was carried out by first, fitting a trendline to the data points of actual drying curves, then forecasting the drying rate back in time. The trend line was forecasted back in time until it reached the "green moisture content" that most would expect coming from green lumber.

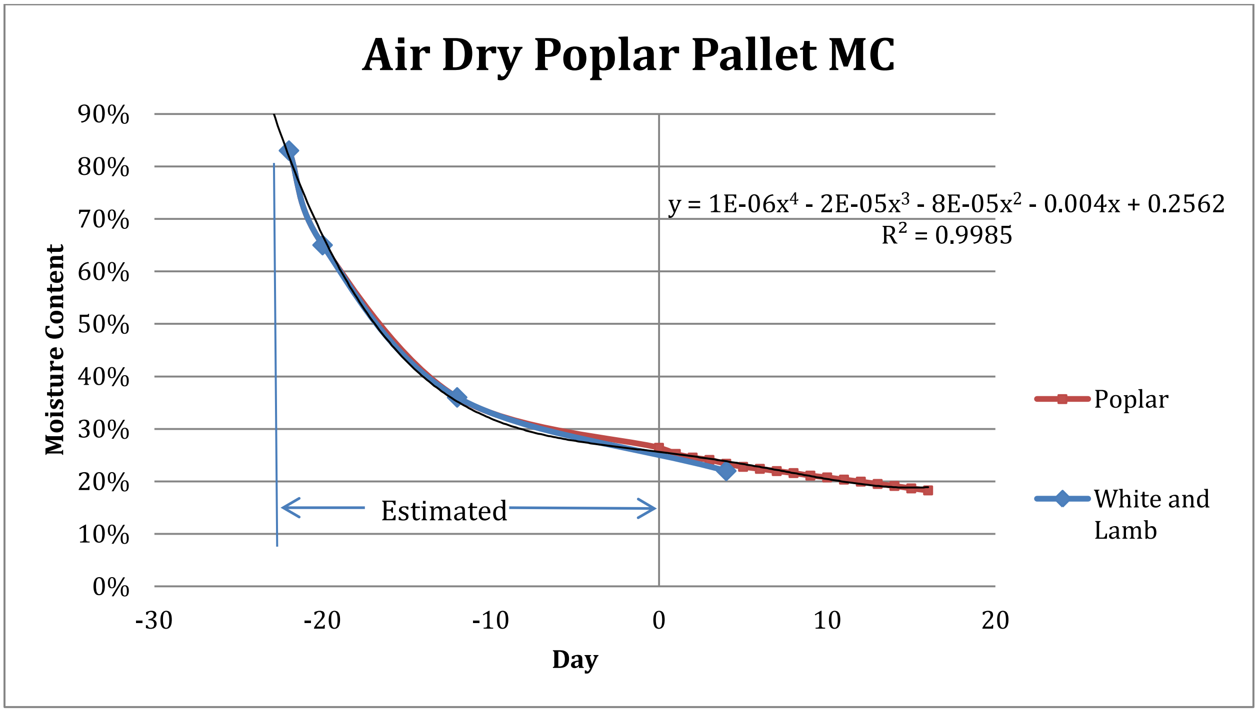

Figure 16: Extrapolated Air Drying Curve Comparison

The R^2 value for the poplar pallets is 0.9985, which means that the curve closely follows the actual drying rate of the pallets. The air drying curve for poplar can be seen in Figure 16. The drying rate decreases as the moisture content decreases. The curves were extrapolated using a regression formula calculated from the trendline. The actual drying data curves were overlapped with drying curves predicted by research findings from White and Lamb's performance evaluation (White and Lamb 2002). The extrapolation was forecast back in time until the curve reached the approximate expected moisture content of "green" yellow poplar pallets. The curve fitting equation for air drying poplar pallets is presented in Equation 6.

$$y = 1e^{-06}\,x^4 - 2e^{-05}x^3 - 0.0004x + 0.2562$$

Equation 6: Air Drying Poplar Pallets

The extrapolated drying curve was compared to the actual drying curves obtained from a pallet air drying test conducted with green pallet material. Figure 16 shows that the extrapolation conducted during this study closely follows the actual drying curve that was obtained from the previous air drying test that was conducted with pallets which had much lower initial moisture content than desired. With both curves closely resembling each other, it means that the extrapolation is fairly accurate in predicting the drying times from green to 25% moisture content.

Using the same techniques described above, the test data was extrapolated to develop a new curve, Figure 17, which can be used to estimate the air drying times for poplar pallets when similar atmospheric conditions are present. From the graph, one can quickly determine that pallets at 83% moisture content will take 23 days to air dry whereas pallets at 50% moisture content take 18 days.

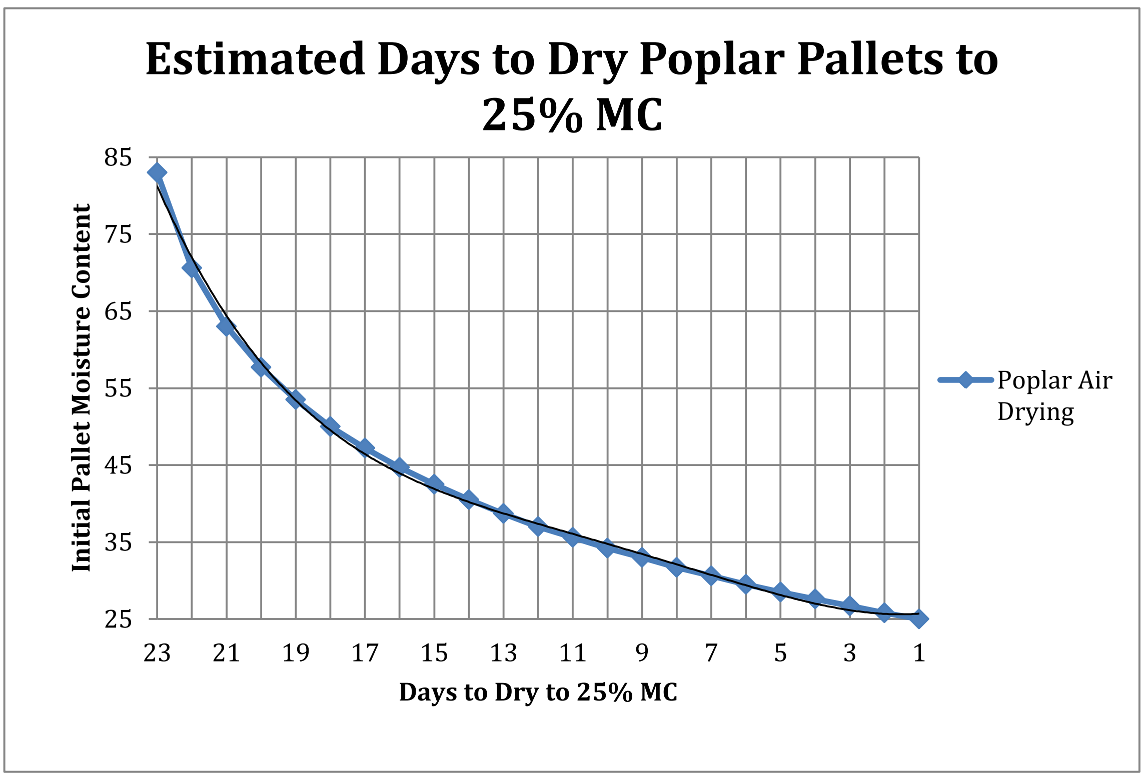

Figure 17: Number of Days Required to Dry Poplar Pallets to 25% Moisture Content based on Green Moisture Content.

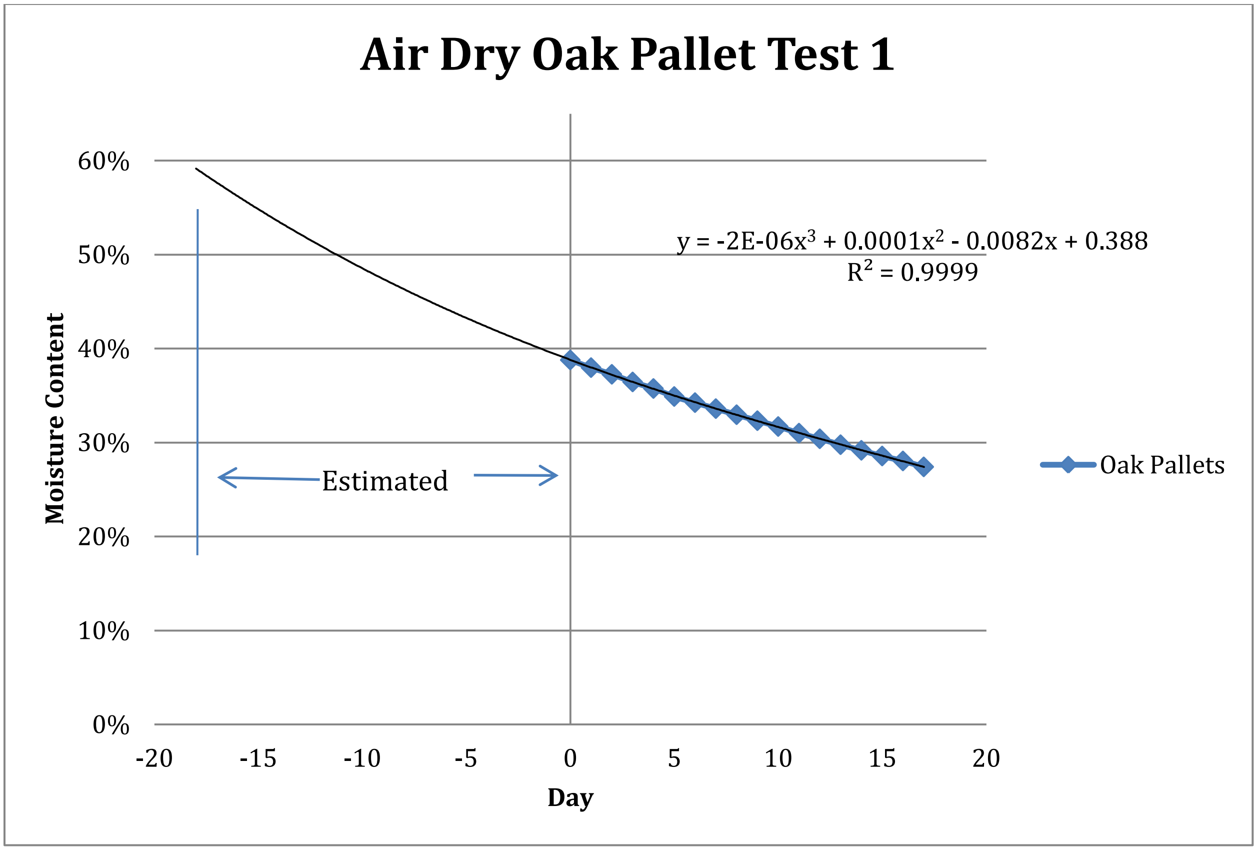

Figure 18: Extrapolated Air Drying Curve for Oak Pallets

The air drying curve for oak pallets can be seen in Figure 18. Just like the poplar pallets, the drying rate decreases at a decreasing rate as the moisture content decreases. The same methods for data extrapolation for yellow-poplar were used for the oak pallets. The resulting R^2 value for the oak pallets was 0.9999, which indicates that the regression curve fits the drying rate very well. The curve fitting equation for air drying oak pallets is presented in Equation 7.

$$y = -2e^{-06}\,x^3 + 0.0001x^2 - 0.0082x + 0.388$$

Equation 7: Air Drying Oak Pallets

4.1.2 Fan Shed

The pallets, twenty oak (red and white oak mix) and twenty yellow-poplar, were placed into the fan sheds, each having their separate shed. The layout of the shed can be seen in Figure 19. The design allowed for two stacks of ten pallets to be stacked side by side in the sheds for a total of 20 pallets. The pallets were centered in front of the fans, and the baffle was lowered, forcing all air from the fans to blow directly through the pallets at a rate of 400 feet per minute. This air-flow rate was measured with an air flow meter. Six measurements were taken for each stack of pallets and the average of all the measurements was 400 feet per minute. The fans were turned off in inclement weather to minimize the possibility of adding moisture back into the pallets.

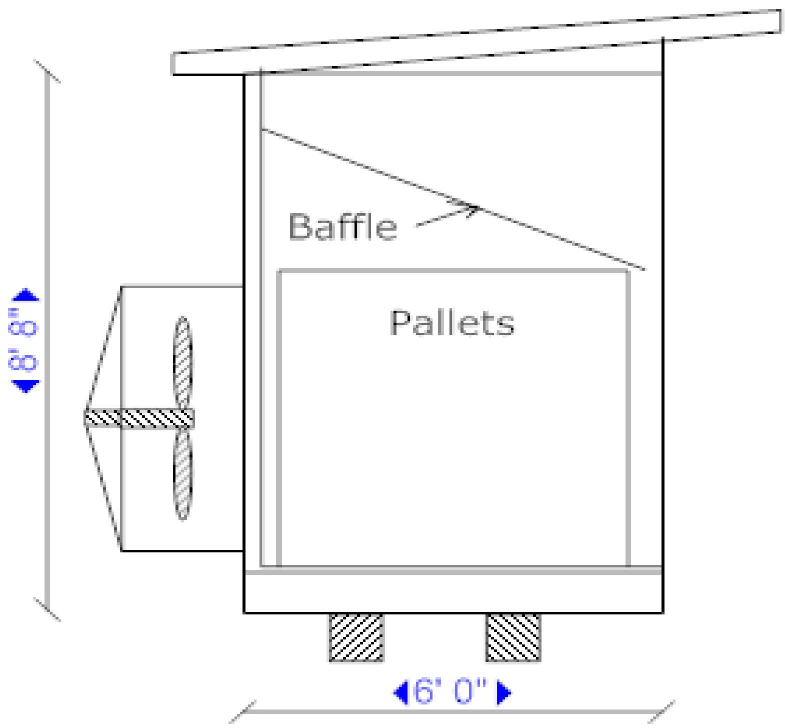

Figure 19: Fan Shed Side Elevation View

Actual Drying Times

The drying curves as seen in Figure 20 and Figure 21 are drying times that were recorded for pallets placed into the fan shed on 9/29/2008.

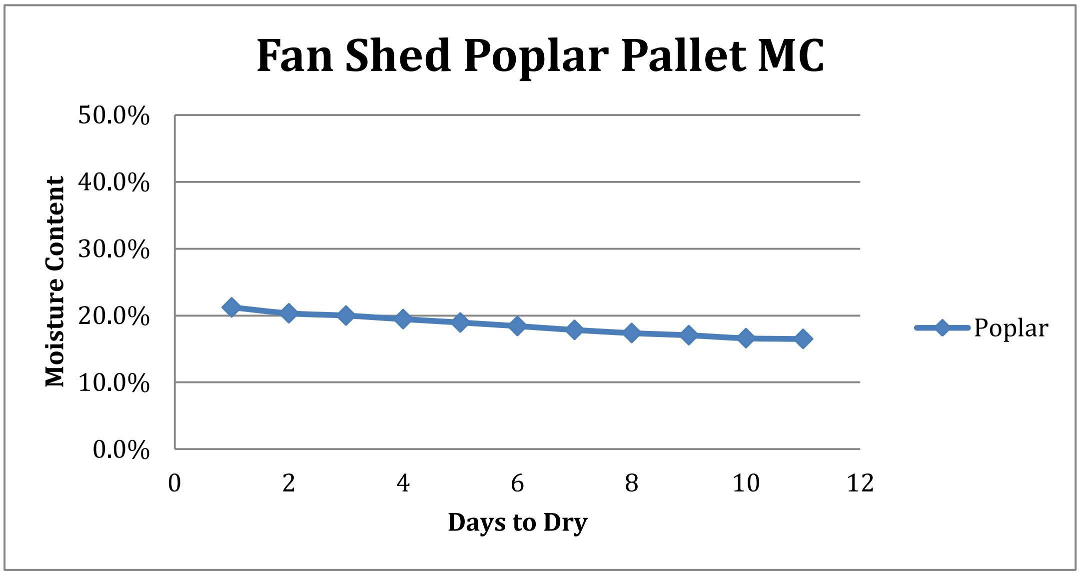

Figure 20: Fan Shed Poplar Drying Curve

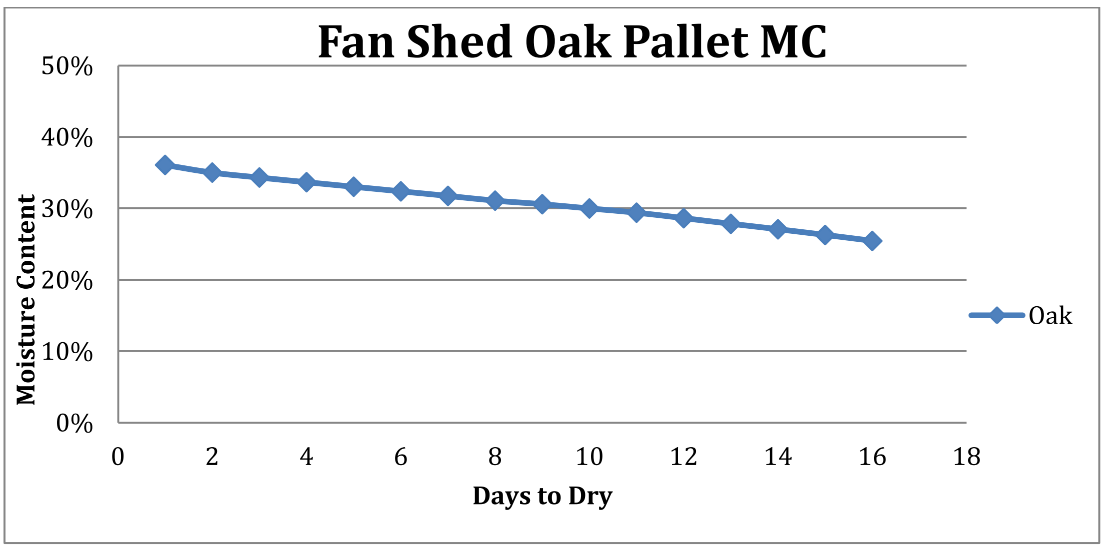

Figure 21: Fan Shed Oak Drying Curve

Extrapolated Drying Times

Since the pallets were not "green" when they arrived as discussed in section 4.1, the drying curves were extrapolated using the same methodology used for the air dried pallets described in the section above to get a close estimate on the full drying time needed from green to 25% moisture content. The pallets were not considered green when they arrived because these pallets were made from log cants, which were below "green" when they were sent to the pallet mill. The extrapolated drying curves for both the oak and the poplar can be seen in Figure 22 and Figure 23. Again, the extrapolations were forecasted back in time until they reached the approximated “green” moisture content for each species. The yellow poplar green moisture content is much higher than the mixed oak, therefore the poplar drying curves had to be forecasted back in time even further than the white oak pallets.

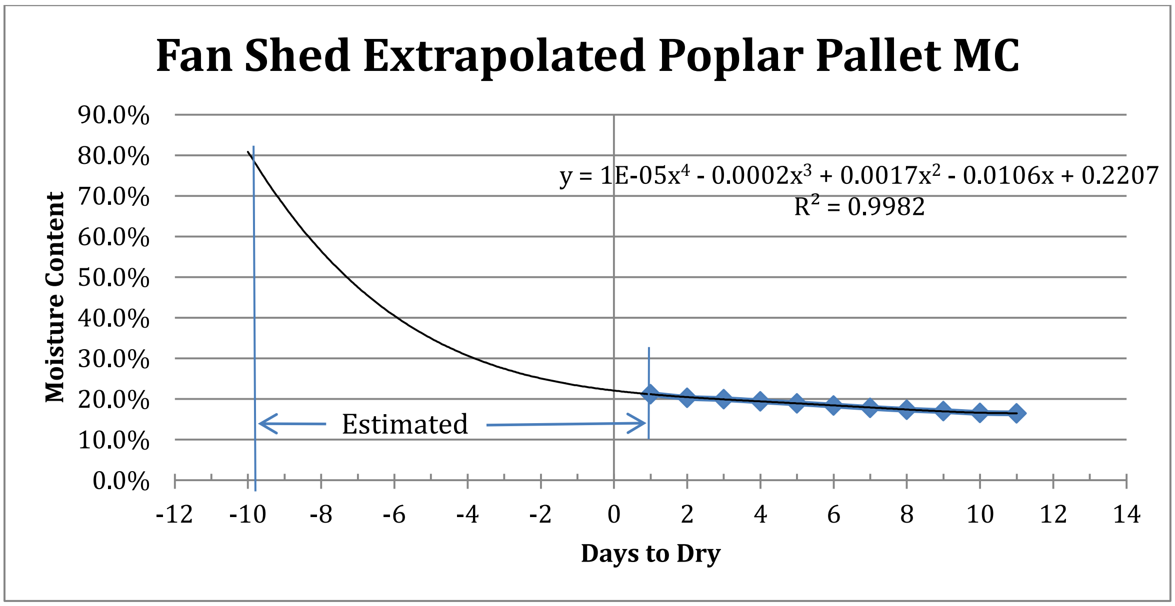

Figure 22: Extrapolated Drying Curve for Poplar

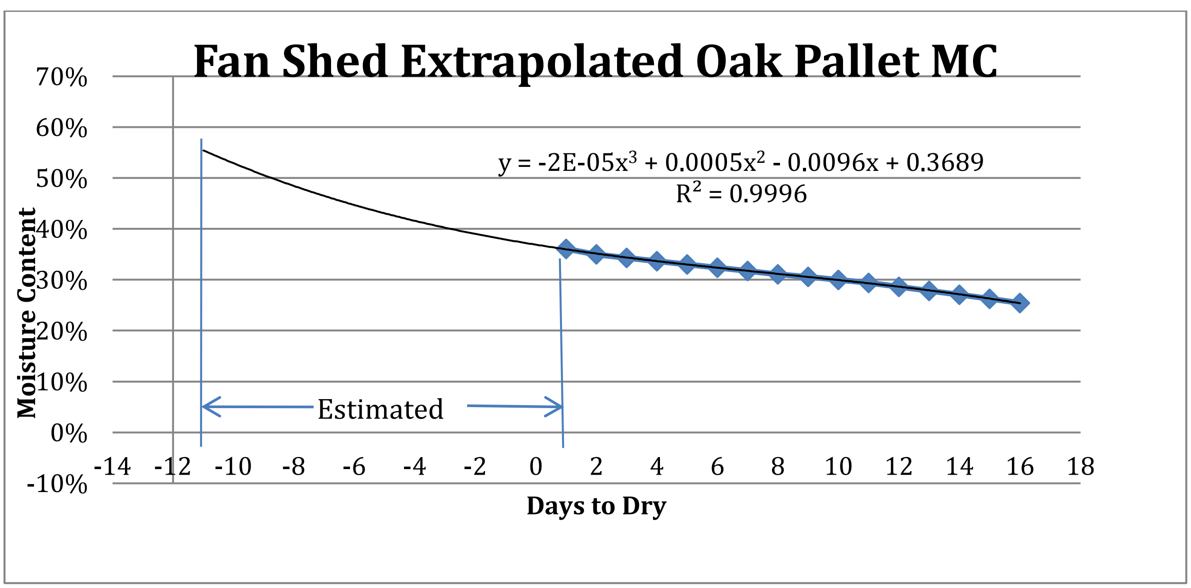

Figure 23: Extrapolated Drying Curve for Oak

4.1.3 Kiln Drying

Four kiln charges were tested to develop a schedule that would dry the pallets with minimal degrade and the most rapid drying time. The schedules that were derived for this test started out as standard hardwood kiln schedules as described in the Dry Kiln Operators Manual (Simpson and Boone, 2001). These starting schedules can be seen in Table 6 and Table 7, which can be found on page 39. After each kiln charge, the pallets were evaluated using the PDS Pallet Component Grades Lumber Characteristic Restrictions (NWPCA 2006) found in Appendix D to determine if the schedule was too harsh or too conservative. The harshness of the schedule was dictated by pallet degrade. As seen in these pallet component grade restrictions, splits in the pallet component parts could not exceed ¼ of the part length. If the split exceeded that length due to drying, the pallet was degraded. Also, if a deckboard contained two open splits at the fasteners on the same end of the board, it was considered a degrade.

Oak Pallets

Since a drying schedule could not be found for pallets, the T4-C2 (Table 7) schedule was used as a starting point for the oak pallets. This schedule was used because the T4-C2 schedule is the drying schedule for 5/4 & 6/4 white oak lumber and the pallet stringers measured slightly thicker than 6/4. Once the pallets that were dried using this schedule were evaluated, it was determined based on the PDS Pallet Component Grades (Appendix D) that this schedule was too advanced for pallets. This schedule caused 15% of the pallets to be degraded, due to open splits at the fasteners. The number of splits that occurred during kiln drying for both the T4-C2 schedule and the conservative schedule can be seen in Table 10.

Table 10: Open Splits at the Fasteners that Occurred in Oak Pallets during Kiln Drying

Oak Kiln T4-C2 Charge		
Pallet No	Splits after Drying	Degrade Pallet?
1	0	N
2	2	N
3	5	Y
4	1	N
5	0	N
6	1	N
7	1	N
8	0	N
9	0	N
10	0	N
11	2	N
12	5	Y
13	7	Y
14	2	N
15	1	N
16	0	N
17	0	N
18	1	N
19	1	N
20	0	N
	% pallets Degraded	15.0%

Oak Kiln Conservative Charge		
Pallet No	Splits after Drying	Degrade Pallet?
1	1	N
2	0	N
3	0	N
4	1	N
5	1	N
6	2	N
7	1	N
8	0	N
9	0	N
10	0	N
11	0	N
12	0	N
13	2	N
14	1	N
15	0	N
16	1	N
17	0	N
18	0	N
19	0	N
20	0	N
	% pallets Degraded	0.0%

Since this schedule dried the pallets too rapidly, a more conservative schedule was developed and tested. The more conservative schedule, seen in Table 11, was modified based on recommendations from the Dry Kiln Operators Manual by decreasing the depression as well as the temperature slightly to slow the drying rate. Since the pallets were dried down to 25% moisture content, there was no need to create steps below 25% moisture content.

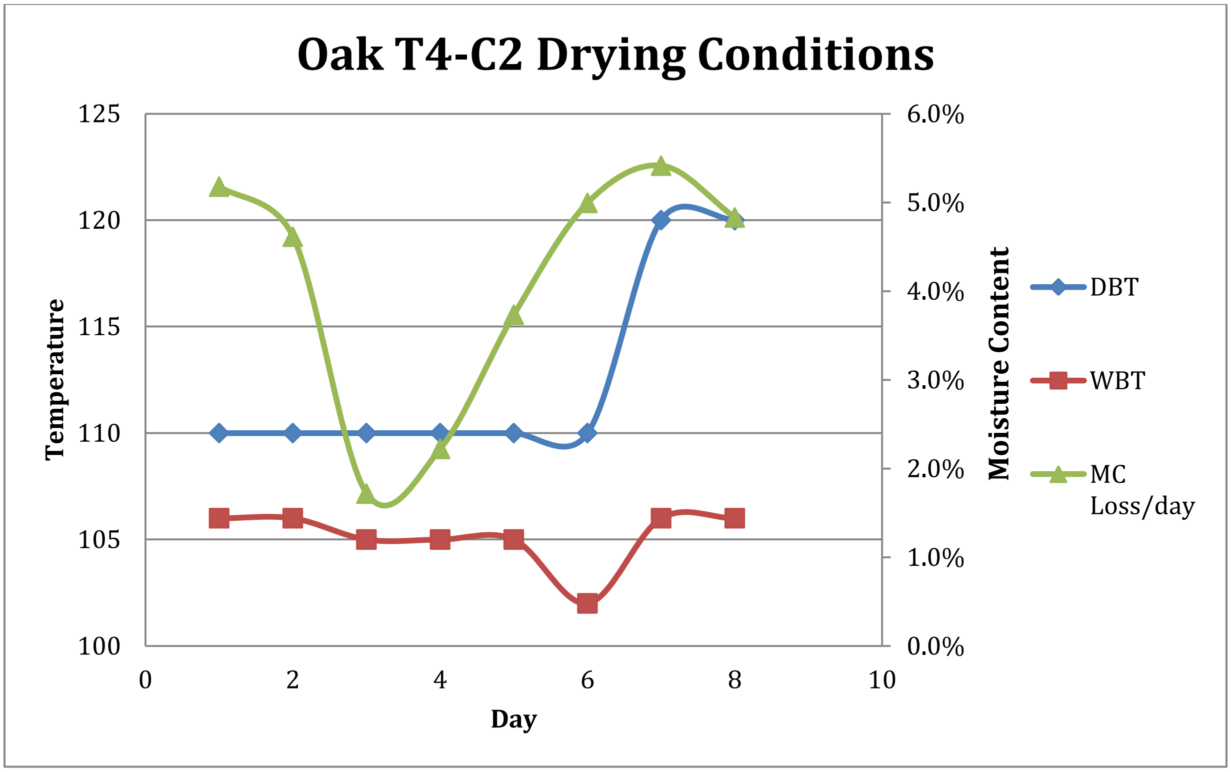

Figure 24: Kiln Conditions and Drying Rate for T4-C2 Kiln Schedule

The excessive drying rate that occurred when using the T4-C2 kiln schedule can be seen in Figure 24 above. The initial and final steps of the kiln schedule created moisture content loss per day that exceeded 5.0%. This excessive drying rate caused some moderate warp that occurred on the pallets that were located closest to the top of the stack.

Table 11: White Oak Conservative Kiln Schedule

White Oak Conservative Kiln Schedule					
Step	% MC	Dry Bulb	Wet Bulb	Depression	EMC
1	Above 50	100	97	3	19
2	50 to 40	100	96	4	17.5
3	40 to 35	100	94	6	15.0
4	35 to 30	110	98	12	10.8
5	30 to 25	110	92	18	8.4

Figure 25 shows the kiln conditions with the drying rate for the white oak conservative kiln schedule that is in Table 11. The drop in moisture content loss per day occurred as the moisture content of the pallets approached the next step in the kiln schedule. Once it reached the moisture content to advance it to the next step, the moisture content loss per day began to increase.

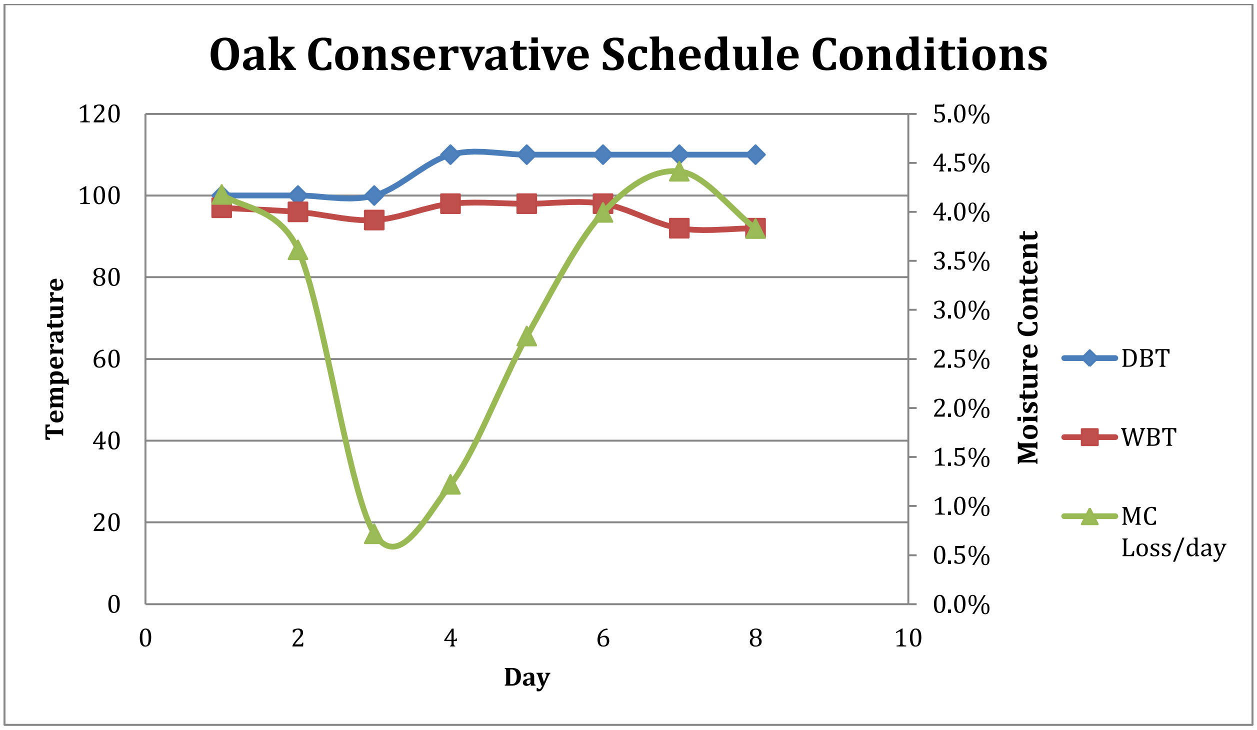

Figure 25: Kiln Conditions and Drying Rate for Oak Pallets

The last oak test, as seen in Figure 25, caused only ten open splits in the deckboards during the drying cycle. The number of splits per pallet can be seen in Table 10. These ten splits alone were not enough of a drying defect to cause a degrade in the pallets based on the MHIA/ANSI/MS1 rules, therefore there was 0% degrade in this kiln charge. The MHIA/ANSI/MH1 section 7.1 (c) states that pallet deckboards with splits greater than one half the length of the deckboard, or a crack one half the width of the deckboard, must be replaced (ANSI 2005). The pallets that experienced splits from drying were at the fasteners. These splits were only several inches in length, nowhere near one half the length of the deckboard. MHIA/ANSI/MH1 section 6.2.4.4 states that nail splits can occur as long as no more than one nail split per connection and not more than one third of the components of the pallet (ANSI

2005). This charge showed some signs of drying defects, such as mild warp, but was conservative enough to cause 0% degrade.

Poplar Pallets

The T11-D4 (Table 6) schedule was used as a starting point for the yellow-poplar pallets. The T11-D4 schedule was used because it is the kiln schedule used for 4/4, 5/4, and 6/4 yellow poplar lumber. After this charge was complete, the pallets were evaluated based on the number of open splits to determine if the schedule was too advanced or too conservative. The kiln conditions and drying rate for this T11-D4 schedule can be seen in Figure 26 below. This kiln schedule, which had an average moisture content loss per day of 8.2% is very conservative for yellow poplar, causing 0% degrade in the pallets, so a more advanced kiln schedule was developed and tested based on recommendations from the Dry Kiln Operators Manual. This more advanced kiln schedule can be seen below in Table 12. This schedule is more advanced than the starting schedule due to the higher dry bulb temperature, as well as a lower initial EMC.

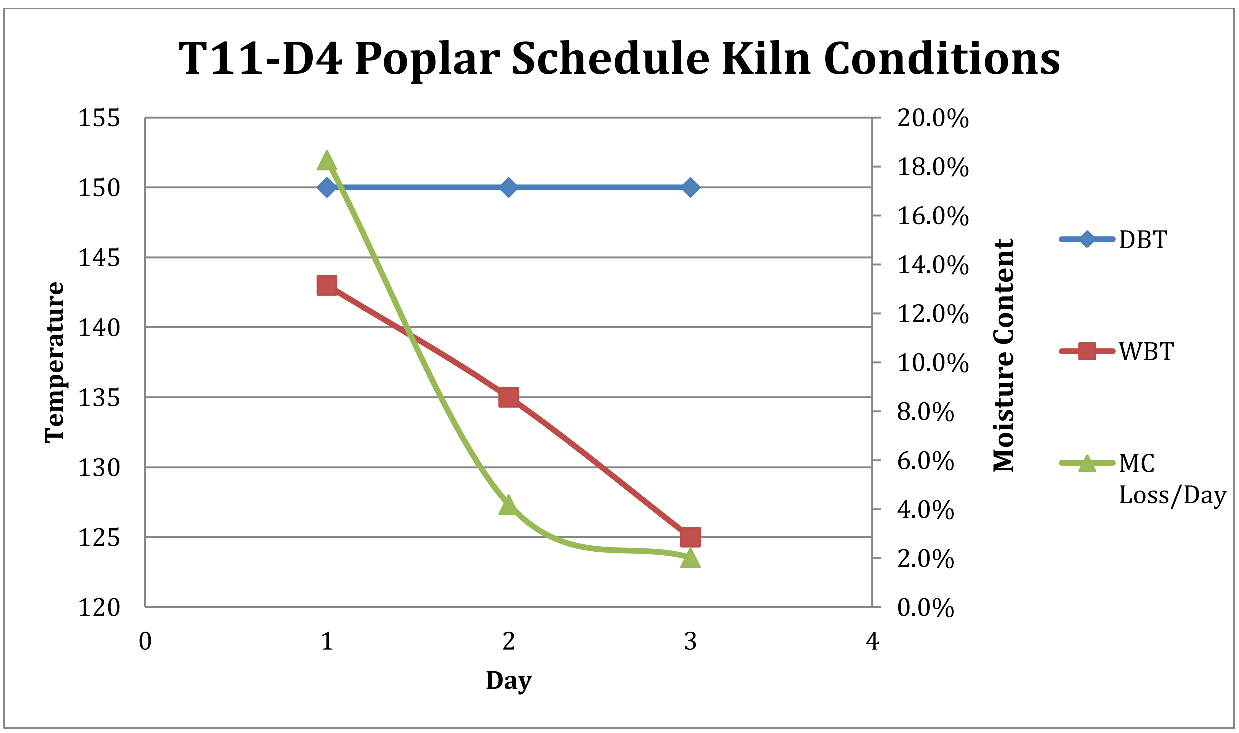

Figure 26: Kiln Conditions and Drying Rate for T11-D4 Schedule

Table 12: Advanced Yellow-Poplar Kiln Schedule

Yellow Poplar Accelerated Kiln Schedule					
Step	**% MC**	**Dry Bulb**	**Wet Bulb**	**Depression**	**EMC**
1	Above 50	155	145	10	11.7
2	50 to 40	155	139	16	9.2
3	40 to 35	155	135	20	8.0
4	35 to 30	155	126	29	6.0
5	30 to 25	165	127	38	4.6
6	25 to 20	165	120	45	3.7

This more advanced schedule decreased the drying time of the poplar pallets but there were more splits in the deckboards of the pallets with the more advanced schedule than there was with the starting schedule. Although there were 11 more splits, they were not large enough or occurred on the same deckboard to cause a pallet to be degraded based on the NWPCA rules. According to the NWPCA rules, in order for a pallet to be degraded, a split that occurs during drying must exceed ¼ of the length of the member. In the deckboards, ¼ of the length of a deckboard is equal to 10” in length. The splits that occurred in this testing never exceeded 7” in length. The kiln conditions and the drying rate of this more advanced schedule can be seen in Figure 27 below. A more rapid test was not conducted because the deckboards showed some signs of rapid drying, other than the splits. The deckboards warped visually more than the previous test and it was assumed that the maximum drying rate had been reached without causing degrade.

The number of open splits per pallet can be seen in Table 13 below. The most advanced poplar schedule did produce 8 more splits than the previous charge, with a total of 19 open splits that occurred during drying at the fasteners, as well as signs of more severe warping.

Table 13: Open Splits that Occurred at Fasteners During Kiln Drying Poplar Pallets

Poplar T11-D4 Charge 1		
Pallet	# of Splits	Degrade?
1	0	N
2	0	N
3	1	N
4	0	N
5	0	N
6	0	N
7	0	N
8	1	N
9	0	N
10	0	N
11	0	N
12	1	N
13	1	N
14	1	N
15	1	N
16	0	N
17	0	N
18	0	N
19	0	N
20	0	N
TOTAL	6	
	% Degraded	0.0%

Poplar Advanced Charge 2		
Pallet	# of Splits	Degrade?
1	0	N
2	2	N
3	1	N
4	1	N
5	0	N
6	1	N
7	1	N
8	0	N
9	1	N
10	0	N
11	2	N
12	2	N
13	1	N
14	2	N
15	1	N
16	0	N
17	1	N
18	1	N
19	2	N
20	0	N
TOTAL	19	
	% Degraded	0.0%

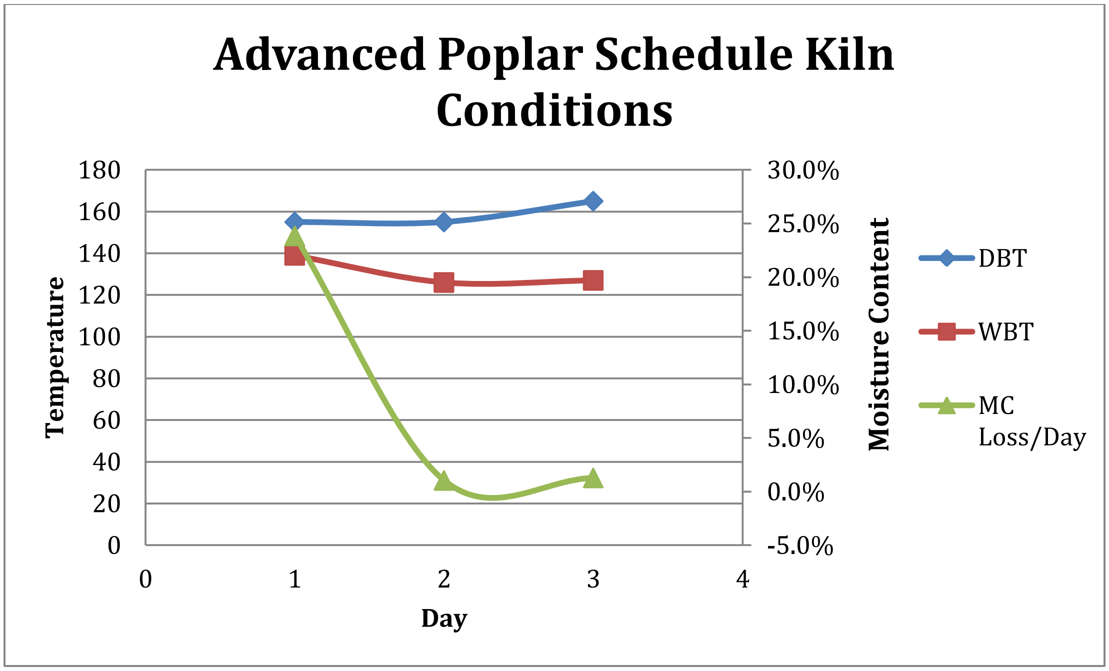

Figure 27: Kiln Conditions and Drying Rate for Advanced Poplar Schedule

4.1.4 Chemical Treatment

A total of 40 pallets were dip treated with a chemical fungicide. Twenty pallets were yellow poplar and twenty were oak. The pallets were placed on the air dry yard immediately after dipping on September 29, 2008. The moisture content for the poplar and oak pallets can be seen in Figure 28.

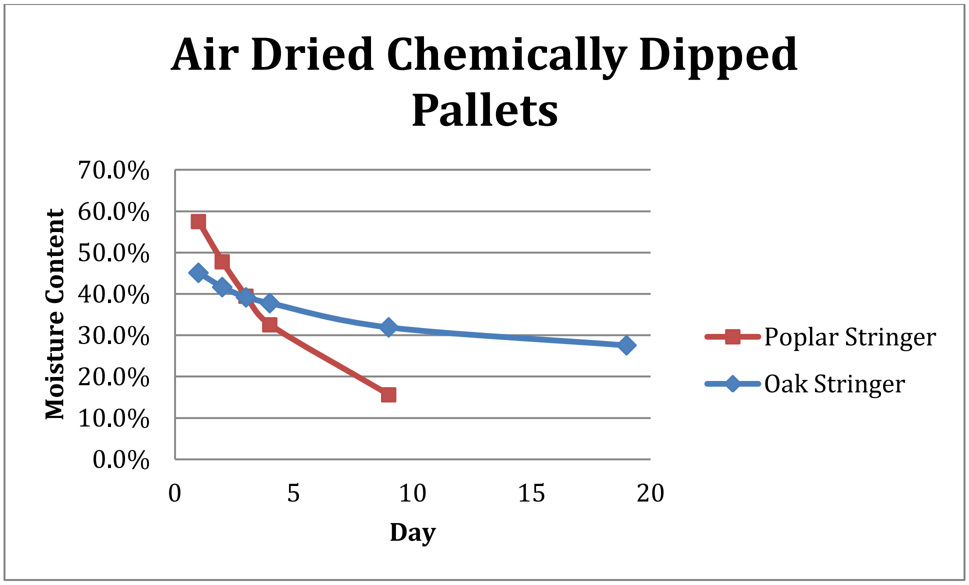

Figure 28: Moisture Content of Chemically Dipped Pallets while Air Drying

4.2 Treatment Evaluation

Two hundred pallets were inoculated by spraying the pallets with an aqueous solution that contained mold spores (Aspergillus, Stachybotrys, and Penicillium) as the pallets were placed in a closed environment for a period of 14 days undisturbed. The temperature and relative humidity inside the trailer was obtained from data loggers placed inside the container just before the doors were shut for the 14 day period. The temperature and relative humidity data can be seen in Figure 29 below. The container that was used was a 40' enclosed trailer that measured 8'-4" in width and 8'-6" in height. The moisture content of the pallets going into the trailer ranged between 14.4 and 24.1% moisture content as shown in Table 14.

Table 14: Moisture Content of Pallets prior to being placed into Enclosed Trailer

	Air Dry Pallets		Dipped Pallets		Fan Shed Pallets		Kiln Dry	
Stringer #	**Poplar**	**Oak**	**Poplar**	**Oak**	**Poplar**	**Oak**	**Poplar**	**Oak**
1	23.9%	21.0%	10.3%	19.6%	15.5%	22.5%	16.5%	24.3%
2	26.5%	14.7%	12.1%	15.1%	11.3%	25.9%	18.2%	23.1%
3	12.5%	20.9%	13.5%	17.9%	16.6%	24.2%	14.9%	21.4%
4	24.4%	16.5%	-	16.8%	14.2%	23.6%	19.4%	24.0%
5	23.9%	23.0%	-	-	-	-	-	-
6	21.6%	25.0%	-	-	-	-	-	-
7	23.9%	17.9%	-	-	-	-	-	-
8	27.7%	22.0%	-	-	-	-	-	-
AVG.	23.1%	20.1%	12.0%	17.4%	14.4%	24.1%	17.3%	23.2%
STD DEV.	4.6%	3.5%	1.6%	1.9%	2.3%	1.4%	2.0%	1.3%

After 14 days, the door was opened on the container and the pallets were inspected for mold using ASTM D-4445 Standard Test Method for Fungicides for Controlling Sapstain and Mold on Unseasoned Lumber. No mold was found to be present on the pallets after the 14 day incubation period therefore, no data is presented for the amount of mold on pallets. This demonstrates that drying pallets to a moisture content between 19% and 24% will prevent mold growth for up to 14 days in an enclosed environment.

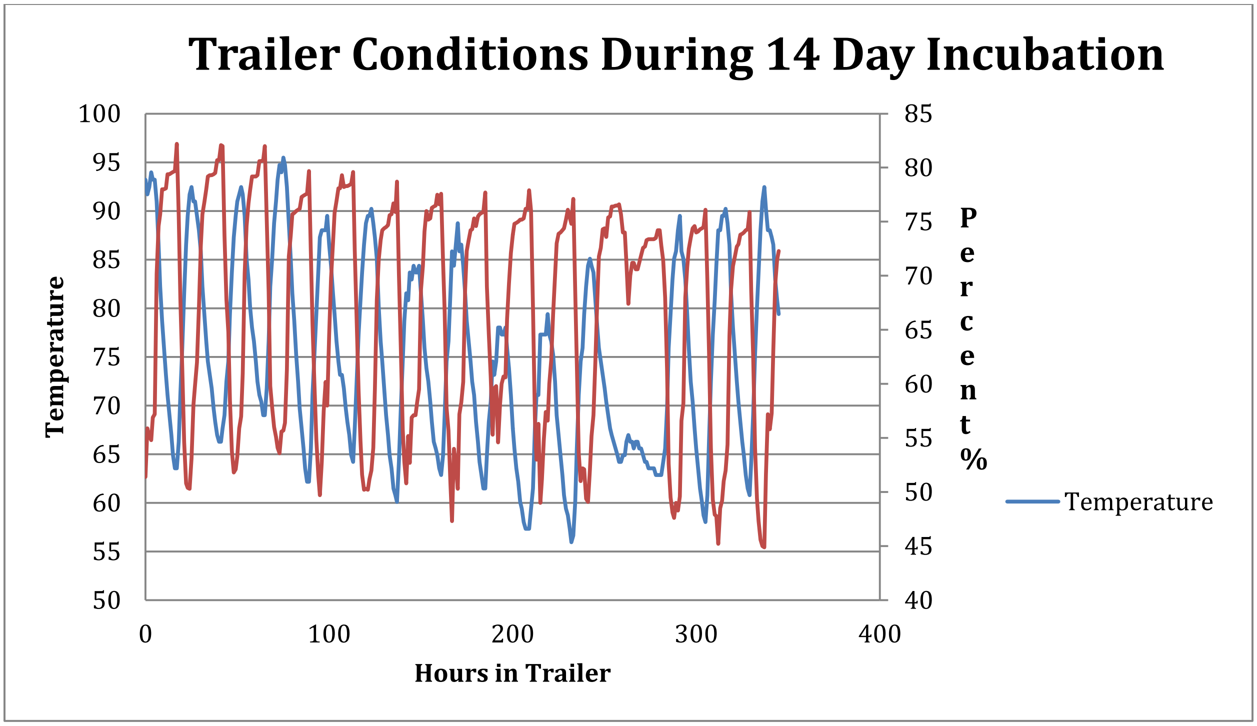

Figure 29: Internal Trailer Conditions during 14 Day Incubation Period

Looking at the temperature and relative humidity from the graph above in Figure 29, notice how when the temperature drops, the humidity increases, and as the temperature starts to rise, the humidity starts to decrease. The time period between 250 and 290 hours on the graph is where the high temperature for the day was 64 degrees and the low was 61, which kept the trailer temperature low for an extended period of time. The dew point inside the trailer was never reached when was loaded with oak pallets (21.0% average moisture content) and poplar pallets (18.3% average moisture content) when left undisturbed for 14 days. With this data, any trailer loaded with pallets of this moisture content under the same environmental conditions should never reach dew point. The average temperature and relative humidity change inside the trailer in a 24 hour time period was 26.1°F and 29.1%, respectively.

4.3 Cost Estimations

The methodology developed by McMillian and Wengert's study, "Drying Eastern Hardwood Lumber" (McMillen and Wengert, 1978) was used in conjunction with Net Present Value (NPV) calculations in order to estimate the cost and evaluate each method. The cost of each mold prevention method was calculated for treatment methods to allow for comparison and a methodology was developed to allow manufacturers to be able to calculate their cost. The costs calculated in this section are limited to the number of pallets tested by each method. Due to economies of scale, the cost of a full size pallet drying facility will not be the same cost as what is calculated below. Although the actual costs will be different, they should be relative to one another.

A list of general assumptions and constants used in the cost calculations for the treatment methods in which they apply can be seen in Table 15. The numbers used are estimations of current prices and values. The estimated values include annual interest rate, estimated land value, tax rate, and insurance rate. These values are assumptions that were kept consistent throughout the entirety of this testing to give a fair comparison of the methods tested.

Table 15: General Assumptions and Constants used in Cost Analysis Formulas.

Cost and Assumptions		
Item Number	**Value**	**Description**
12	0.56	Number of mbf in 40 pallets
13	0.08	Annual Interest Rate (Assumption)
33	200	Land Area (sq. ft.)
37	8	Estimated Land Value ($/sq.ft.) (Assumption)
48	0.08	Tax Rate
49	0.05	Insurance Rate
50	0.08	Stacking Time (Mbf/hr)
51	10	Hourly Stacking Cost
52	0.56	Forklift time (mbf/hr)
53	10	Hourly Forklift Cost
54	0.25	Time spent each day checking lumber (hr)
55	10	Hourly Wage Rate for Kiln operator
61	0.05898	Electrical Cost (VT Campus)
62	0.000714	Estimated Price of Lumber
63	0.05	Estimated Degrade
64	0.56	Average Daily Volume Lumber, mbf

4.3.1 Air Drying

The cost associated with air drying was determined by calculating the inventory cost to hold and dry 40 pallets for the time period required for the pallets to reach 25% moisture content. These values were calculated using the methodology obtained from Appendix C. Land values, as well as taxes were taken into consideration for making this cost aspect as accurate as possible as seen in

Table 16. McMillen and Wengert provide an analysis of cost of an air dry facility that was used in determining the land values and tax that will be involved in this study (McMillen and Wengert 1978). The cost analysis of an air dry yard can be seen in Table 17. The list of assumptions for calculating the air drying cost can be seen below in Table 16.

Table 16: List of Assumptions and Constants for Air Drying Calculations

Air Drying Cost Assumptions and Constants		
Item Number	**Value**	**Description**
12	0.56	Number of mbf in 40 pallets
13	0.08	Estimated Annual Interest Rate
33	200	Land Area (ft^2)
37	8	Estimated Land Value ($\$/ft^2$)
48	0.08	Tax Rate
49	0.05	Insurance Rate
51	10	Hourly stacking cost
62	0.000714	Average Price of Lumber
63	0.05	Average Degrade
64	0.56	Average daily volume lumber mbf

Using the information in Appendix C, the values were placed on the line in Table 17 on the same line as the corresponding number in the Appendix. Note that when using this general approach for specific cases, not all items will have charges or costs. The formulas that contain null values are not included in the final total.

Table 17: Air Drying Cost Assessment used with Appendix C

Item #	Value	Item #	Value	Item #	Value
1		23		45	
2		24		46	0.0008
3		25		47	0.0008
4		26		48	0.08
5		27		49	0.05
6		28		50	0.08
7		29		51	10
8		30		52	0.56
9		31		53	10
10		32		54	
11		33	200	55	
12	0.56	34		56	
13	0.08	35		57	
14		36	200	58	
15		37	8	59	
16		38	2000	60	
17		39		61	
18		40		62	0.56
19		41		63	0.05
20		42	2000	64	0.56
21		43		65	
22		44		66	

The formulas in Table 18 have numbers in the parentheses that correspond to the numbers in Table 17. Once the values are input into the formulas, the output is the cost of the air drying yard per year. The formulas that contain items that were left blank on the input table are not factored into the sum of the total.

Table 18: Cost Accounting Approach

Basis for Calculation	Formula
Amortization for direct investment	(1)/[(7)*(12)]
	(2)/[(8)*(12)]
	(3)/[(9)*(12)]
	(4)/[(10)*(12)]
	(5)/[(11)*(12)]
Interest on direct investment	(6)/[(13)*(12)]
Amortization values for air-drying investments	(14)/[(22)*(12)]
	(15)/[(23)*(12)]
	(16)/[(24)*(12)]
	(17)/[(25)*(12)]
	(18)/[(26)*(12)]
	(19)/[(27)*(12)]
	(20)/[(28)*(12)]
Interest on air-drying investments	[(21)*(13)]/12
Yard maintenance & repair	[(29)+(30)+(31)+(32)]/(12)
Land interest	[(36)*(37)*(13)]/(12)
Taxes on kiln and air drying yard	[(42)*(48)]/(12)
total insurance	[(47)*(49)]/(12)
stacking cost	(50)*(51)
forklift cost	(52)*(53)
kiln labor	[(54)*(55)*(66)]/(65)
kiln maintenance	(56)/(12)
office overhead	(57)/(12)
energy cost	[(58)*(59)+(60)*(61)]/(12)
interest on inventory	[(62)*(64)*(13)]/(12)
degrade	(62)*(63)
	TOTAL

The values for the air drying yard were put into the formulas and the results are shown in Table 19. The numbers below are calculated for a total of 40 pallets that were air dried during this project. Using this information for 40 pallets at a price to air dry at $1.43 per day, it took 20 days for the oak pallets to dry from 38.8% to 25% moisture content, which produces a total cost of 82.40 to air dry them, which is $1.03 per pallet.

Table 19: Cost Accounting Approach for Air Drying Pallets

Basis for Calculation	Formula	Output
Amortization for direct investment	(1)/[(7)*(12)]	
	(2)/[(8)*(12)]	
	(3)/[(9)*(12)]	
	(4)/[(10)*(12)]	
	(5)/[(11)*(12)]	
Interest on direct investment	(6)/[(13)*(12)]	
Amortization values for air-drying investments	(14)/[(22)*(12)]	
	(15)/[(23)*(12)]	
	(16)/[(24)*(12)]	
	(17)/[(25)*(12)]	
	(18)/[(26)*(12)]	
	(19)/[(27)*(12)]	
	(20)/[(28)*(12)]	
Interest on air-drying investments	[(21)*(13)]/12	
Yard maintenance & repair	[(29)+(30)+(31)+(32)]/(12)	
Land interest	[(36)*(37)*(13)]/(12)	228.57
Taxes on kiln and air drying yard	[(42)*(48)]/(12)	285.71
total insurance	[(47)*(49)]/(12)	
stacking cost	(50)*(51)	0.8
forklift cost	(52)*(53)	0.56
kiln labor	[(54)*(55)*(66)]/(65)	
kiln maintenance	(56)/(12)	
office overhead	(57)/(12)	
energy cost	[(58)*(59)+(60)*(61)]/(12)	
interest on inventory	[(62)*(64)*(13)]/(12)	0.0448
degrade	(62)*(63)	0.0000357
	TOTAL ($)	520.69
	Cost per day	**$1.43**

It was estimated that the cost to air dry pallets with the above assumptions is approximately $1.43 per day to operate the air dry yard. Using this value and the trying times observed, a cost per pallet can be compared.

4.3.2 Fan Shed

Fan sheds were constructed to test drying times and assist in estimating the costs of forced air drying. Since two different species of wood was dried, two fan sheds were constructed, enabling two completely independent starting and ending times. The electrical cost were calculated for each fan shed and can been seen in Table 20.

Table 20: Electrical cost of each fan shed

Oak Pallets			Poplar Pallets		
Watts/hr	480		**Watts/hr**	480	
Total hours run	552		**Total hours run**	525	
Number of kwh	264.96		**Number of kwh**	252	
Location	**Price kwh ($)**	**Cost 2 fans ($)**	**Location**	**Price kwh ($)**	**Cost 2 fans ($)**
VT Campus	0.05898	31.25	VT Campus	0.05898	29.73
New England	0.13450	71.27	New England	0.13450	67.79
Mid-Atlantic	0.08360	44.30	Mid-Atlantic	0.08360	42.13
East North Central	0.06600	34.97	East North Central	0.06600	33.26
West North Central	0.05670	30.05	West North Central	0.05670	28.58
South Atlantic	0.06660	35.29	South Atlantic	0.06660	33.57
East South Central	0.06110	32.38	East South Central	0.06110	30.79
West South Central	0.08520	45.15	West South Central	0.08520	42.94
Mountain	0.06500	34.44	Mountain	0.06500	32.76
Pacific Southwest	0.08670	45.94	Pacific Southwest	0.08670	43.70

Note: This was for 20 pallets of each species and two 110v fans.

The cost data in Table 20 was calculated based on drying times that were derived from the extrapolated drying curves (see Figure 22 and Figure 23) because the poplar pallets were below the desired 25% moisture content at the start of testing. The electricity cost used to calculate these values were averages from September 2008 based on Industrial costs from the Department of Energy (DOE) from many regions around the US (DOE 2008).

The electrical energy cost was calculated by determining exactly how many kilowatt hours were used in the test. The KWH can then be multiplied by the electrical cost which varies depending upon geographic location (see Table 20). The amount of KWH was calculated by knowing the wattage of the fans and the time period the fans are running. Calculating the amount of kWh can be done using the following equation:

kWh = [(# of watts) x (run time in hours)] / 1000.

Depending upon the size of the fan shed will determine the number of fans required to efficiently circulate air throughout the shed. Since there was only a single stack of pallets, small single phase 110 volt fans measuring 36" were used in this study. These fans produced an air velocity averaging 400 feet per minute through the single stacks of pallets. In a full size fan shed, since the fans are forcing air through multiple stacks of pallets, multiple fans are needed simply because of the mass of air that is needed to be moved. Often, fan sheds will have a wall of fans that span the center of the building and pallets are stacked on both sides of the wall. The fans reverse every few hours changing direction of air flow, allowing for more uniform drying throughout the shed.

The same cost accounting approach that was used in section 4.3.2 was used for accurately estimating the cost of running the fan sheds during the study. The values that were used for this calculation can be found in Table 22. The costs of operating the fans are included in the calculations below. The price per kWh that was used for this calculation is 0.05898, which is the cost of electricity charged by the Virginia Tech Electrical Services here on the Virginia Tech Campus. The list of assumptions and constants that were used in the fan shed cost analysis can be found in Table 21.

Table 21: Assumptions and Constants for Fan Shed Cost Analysis

Fan Shed Cost Assumptions and Constants		
Item Number	**Value**	**Description**
1	750	Total cost of fan shed
7	12	Amortization period
12	0.56	Number of mbf in 40 pallets
13	0.08	Estimated Annual Interest Rate
33	100	Land Area (ft^2)
37	8	Estimated Land Value ($/$ft^2$)
38	800	Taxable land value
39	750	Taxable buildings
42	1550	Total Taxable Items
44	750	Insurable buildings
46	0.0448	Value in Lumber
48	0.08	Tax Rate
49	0.05	Insurance Rate
50	0.08	Stacking Time (0.08 mbf per hour)
51	10	Hourly stacking cost
52	0.56	Forklift time
53	10	Hourly forklift cost
54	0.25	15 minutes to check fan sheds
60	265	Annual electrical usage kWh
61	0.05898	electrical cost ($/kWh)
62	0.56	Estimated Price of Lumber
63	0.05	Average Degrade
64	0.56	Average daily volume lumber mbf

Table 23 shows the results of the cost assessment using the variables for fan shed drying using the assumptions and constants that are in the table above.

Table 22: Fan Shed Cost Assessment used with Appendix C

Item #	Value	Item #	Value	item #	Value
1	750	23		45	
2		24		46	0.0448
3		25		47	750.04
4		26		48	0.08
5		27		49	0.05
6	750	28		50	0.08
7	12	29		51	10
8		30		52	0.56
9		31		53	10
10		32		54	0.25
11		33	100	55	
12	0.56	34		56	
13	0.08	35		57	
14		36	100	58	
15		37	8	59	
16		38	800	60	265
17		39	750	61	0.05898
18		40		62	0.28
19		41		63	0.05
20		42	1550	64	0.56
21		43		65	
22		44	750	66	

Table 23: Cost Accounting Approach for Fan Shed Drying Pallets

Basis for Calculation	Formula	Output
Amortization for direct investment	(1)/[(7)*(12)]	111.61
	(2)/[(8)*(12)]	
	(3)/[(9)*(12)]	
	(4)/[(10)*(12)]	
	(5)/[(11)*(12)]	
Interest on direct investment	(6)/[(13)*(12)]	33.60
Amortization values for air-drying investments	(14)/[(22)*(12)]	
	(15)/[(23)*(12)]	
	(16)/[(24)*(12)]	
	(17)/[(25)*(12)]	
	(18)/[(26)*(12)]	
	(19)/[(27)*(12)]	
	(20)/[(28)*(12)]	
Interest on air-drying investments	[(21)*(13)]/12	
Yard maintenance & repair	[(29)+(30)+(31)+(32)]/(12)	
Land interest	[(36)*(37)*(13)]/(12)	114.29
Taxes on kiln and air drying yard	[(42)*(48)]/(12)	221.43
total insurance	[(47)*(49)]/(12)	66.99
stacking cost	(50)*(51)	0.8
forklift cost	(52)*(53)	5.6
kiln labor	[(54)*(55)*(66)]/(65)	
kiln maintenance	(56)/(12)	
office overhead	(57)/(12)	
energy cost	[(58)*(59)+(60)*(61)]/(12)	27.91
interest on inventory	[(62)*(64)*(13)]/(12)	0.0224
degrade	(62)*(63)	0.03
	TOTAL ($)	582.30
	Cost per day	**$1.60**

The cost per day is the amount it cost to dry the pallets in a fan shed, regardless of the initial pallet moisture content. It was estimated that the cost per day to dry a pallet in the fan shed was $1.60. The cost of the sheds and electricity used lead the daily cost to be approximately 11% higher than air drying. However, for pallets with a moisture content above fiber saturation point, the daily drying rate is 60% faster.

The extrapolated data shows the oak pallets took 23 days to dry in the fan shed, 23 days x \$1.60 per day = \$36.80. This 36.80 dollars divided among the total amount of oak pallets yields \$36.80/20 pallets = \$1.84 per pallet to dry from green to 25% moisture content.

The extrapolated data shows the poplar pallets took 21.88 days to dry in the fan shed, 21.88 x \$1.60 per day = \$35.00. This 35.00 dollars divided among the total amount of poplar pallets yields \$35.00/20 = \$1.75 per pallet to dry from green to 25% moisture content.

4.3.3 Kiln Drying

The energy cost was calculated by determining the amount of Btu's required to treat the pallets in the dry kiln. The amount of Btu's lost during the venting cycle of the kiln, as well as the Btu's lost through the kiln walls were also calculated. This loss in BTU's must be accounted for when calculating cost because every BTU that is used must be paid for.

The heat loss through the walls was calculated using Equation 4 to develop Table 24 below. The dry kiln that was used in this study had the dimensions of 10'(w) x 10'(l) x 9'(h) which gives a total square footage of wall, ceiling, and floor a measurement of 560 ft^2. This data was based on average air temperature that was surrounding the dry kiln during the charge, and it assumed an overall heat transfer coefficient (U_i) of 0.012. The grand total is the sum of all "q" values. As the temperature inside the kiln increases, the Btu loss through the kiln walls also increases. The last day (6) the q value is small because the charge only ran for 12 hours, instead of the 24 hours like the other days.

Venting losses in a dry kiln are the amount of energy lost due to opening and closing the vents to maintain proper temperature and relative humidity inside the chamber. The venting losses for the oak kiln schedule can be seen in Table 25. This data was calculated using Equation 5 and the average daily temperature and absolute humidity for each day.

Table 24: Kiln Btu's and Cost for Poplar Pallets

Volume	SG	ρ H_2O	λ (Btu/lb)	M_0	M_f	q_a
23.3	0.41	62.4	66.51	39.2%	23.1%	95,812

Heat Lost through Kiln Walls (Btu)						
Day	U_i	A_i	t_2	t_1	Q_i	q
1	0.058	560	160	48	12	43,427
2	0.058	560	160	34	24	97,711
3	0.058	560	165	32	24	103,140
4	0.058	560	165	34	12	50,794
					TOTAL (Q)	**295,073**

Venting Losses for Conservative Poplar Schedule 2/7/09 – 2/14/09						
Day	t_1	t_2	H_1	H_2	Venting Losses Btu/min	Daily Venting Losses
1	48	160	0.007106	0.128164	226	162,865
2	34	160	0.003614	0.09609	331	238,166
3	32	165	0.002573	0.09126	363	261,586
4	34	165	0.003614	0.069702	481	346,485
				SUM	**1402**	1,009,103

Total BTU's required for Charge		
	One KW Cost	**$ 0.05898**
	BTU/KW	**3,400**
	KW Used	**411.76**
	Total Cost	**$ 24.29**

(Total BTU's required for Charge: **1,399,988**)

Table 25: Kiln Btu and cost for Oak Pallets

Charge	Volume	SG	ρ H_2O	M_0	M_f	q_a
1	23.3	0.617	62.4	50.9%	24.2%	239,730

Heat Lost through Kiln Walls (Btu)						
Day	U_i	A_i	t_2	t_1	Q_i	q
1	0.058	560	100	68	24	24,816
2	0.058	560	100	68	24	24,816
3	0.058	560	100	68	24	24,816
4	0.058	560	100	68	24	24,816
5	0.058	560	100	68	24	24,816
6	0.058	560	110	68	24	32,570
7	0.058	560	110	68	24	32,570
8	0.058	560	110	68	12	16,285
					TOTAL (Q)	**205,504**

Day	t_1	t_2	H_1	H_2	Venting Losses (Btu/min)	Daily Venting Losses (Btu)
1	42	100	0.003764	0.038496	406	291,996
2	54	100	0.005840	0.036998	360	259,227
3	43	100	0.004565	0.036998	427	307,790
4	52	100	0.006009	0.036998	378	272,064
5	51	100	0.006511	0.036998	392	282,590
6	48	110	0.003888	0.037562	447	322,021
7	45	110	0.003152	0.028963	611	439,780
8	46	110	0.003275	0.028963	604	435,195
				SUM	**3626**	**2,610,663**

TOTAL Btu's Required for Charge	**3,055,898**
One KW Cost	**0.05898**
BTU/KW	**3,400**
KW Used	**898.79**
Total Cost	**$ 53.01**

The above calculations were used in the drying cost assessment (found below) that was used for this study. The values used in the remainder of the assessment were estimated values that were consistent with the assessment for air drying and fan shed drying. The input values can be found in Table 26 and the results of the analysis can be found in Table 27.

Several assumptions were made about the kiln analysis. The first assumption is that the kiln is operating at 100% efficiency. The second assumption that was made for the calculations was 3,400 btu's per kilowatt. This conversion can be seen in Table 24 and Table 25 earlier in this section.

Table 26: Kiln Drying Cost Assessment used with Appendix C

Item #	Value	Item #	Value	item #	Value
1		**23**		**45**	
2	10000	**24**		**46**	0.0448
3		**25**		**47**	10000.04
4		**26**		**48**	0.08
5		**27**		**49**	0.05
6	10000	**28**		**50**	0.08
7		**29**		**51**	10
8	36	**30**		**52**	0.56
9		**31**		**53**	10
10		**32**		**54**	0.25
11		**33**		**55**	10
12	0.56	**34**		**56**	500
13	0.08	**35**	850	**57**	
14		**36**	850	**58**	
15		**37**	8	**59**	
16		**38**	6800	**60**	411
17		**39**		**61**	0.05898
18		**40**	10000	**62**	0.28
19		**41**		**63**	0.05
20		**42**	16800	**64**	0.28
21		**43**	10000	**65**	0.28
22		**44**		**66**	6

Table 27: Cost Accounting Approach for Kiln Drying Pallets

Basis for Calculation	Formula	Output
Amortization for direct investment	(1)/[(7)*(12)]	
	(2)/[(8)*(12)]	496.03
	(3)/[(9)*(12)]	
	(4)/[(10)*(12)]	
	(5)/[(11)*(12)]	
Interest on direct investment	(6)/[(13)*(12)]	448.00
Amortization values for air-drying investments	(14)/[(22)*(12)]	
	(15)/[(23)*(12)]	
	(16)/[(24)*(12)]	
	(17)/[(25)*(12)]	
	(18)/[(26)*(12)]	
	(19)/[(27)*(12)]	
	(20)/[(28)*(12)]	
Interest on air-drying investments	[(21)*(13)]/12	
Yard maintenance & repair	[(29)+(30)+(31)+(32)]/(12)	
Land interest	[(36)*(37)*(13)]/(12)	971.43
Taxes on kiln and air drying yard	[(42)*(48)]/(12)	2400.00
total insurance	[(47)*(49)]/(12)	892.86
stacking cost	(50)*(51)	0.8
forklift cost	(52)*(53)	0.56
kiln labor	[(54)*(55)*(66)]/(65)	4464.29
kiln maintenance	(56)/(12)	892.857
office overhead	(57)/(12)	
energy cost	[(58)*(59)+(60)*(61)]/(12)	43.29
interest on inventory	[(62)*(64)*(13)]/(12)	0.0112
degrade	(62)*(63)	0.03
	TOTAL ($)	10615.19
	Cost per day	**$29.08**

It was estimated that the cost per day to dry a pallet in the kiln was $29.08 per day. For the poplar pallets, this totals $116.32 for the charge, and equaling $5.82 per pallet to kiln dry the pallets from 40% to 25% moisture content. For the oak pallets, the cost for the entire charge is $232.64, which yields a per pallet cost of $11.63 to kiln dry pallets from 50% to 25% moisture content. While kiln drying is the most expensive process, it also provides the fastest drying times for both species (8 days for oak and 4 days for poplar) which is 4.6 times faster for oak and 4.3 times faster for yellow poplar.

4.3.4 Chemical Treatment

The chemically dipped pallets had to also be air dried, which led the cost of chemically dipping pallets to be the same as the cost of air drying, with additional cost of the chemical and the amount of time that was physically spent dipping the pallets. The cost can be seen in Table 30. The pallets were dipped while still green and then placed onto the air dry yard. The cost of the chemical just to dip the pallets into the biocide averaged $0.20 per pallet. This is an average of several manufacturing facilities that chemically treat pallets which was obtained from the supplier of the chemicals used in this study. The labor involved in dipping the pallets was accounted for in the cost analysis on Table 28.

Table 28: Chemical Cost analysis using Appendix C

Item #	Value	Item #	Value	item #	Value
1		23		45	
2		24		46	8.000E-04
3		25		47	8.000E-04
4		26		48	0.08
5		27		49	0.05
6		28		50	0.02
7		29		51	10
8		30		52	1.12
9		31		53	10
10		32		54	
11		33	200	55	
12	0.56	34		56	
13	0.08	35		57	
14		36	200	58	
15		37	8	59	
16		38	2000	60	
17		39		61	
18		40		62	0.000714
19		41		63	0.05
20		42	2000	64	1.12
21		43		65	
22		44		66	

Table 29: Cost Accounting Approach for Chemically Dipping Pallets

Basis for Calculation	Formula	Output
Amortization for direct investment	(1)/[(7)*(12)]	
	(2)/[(8)*(12)]	
	(3)/[(9)*(12)]	
	(4)/[(10)*(12)]	
	(5)/[(11)*(12)]	
Interest on direct investment	(6)/[(13)*(12)]	
Amortization values for air-drying investments	(14)/[(22)*(12)]	
	(15)/[(23)*(12)]	
	(16)/[(24)*(12)]	
	(17)/[(25)*(12)]	
	(18)/[(26)*(12)]	
	(19)/[(27)*(12)]	
	(20)/[(28)*(12)]	
Interest on air-drying investments	[(21)*(13)]/12	
Yard maintenance & repair	[(29)+(30)+(31)+(32)]/(12)	
Land interest	[(36)*(37)*(13)]/(12)	228.57
Taxes on kiln and air drying yard	[(42)*(48)]/(12)	285.71
total insurance	[(47)*(49)]/(12)	0.00
stacking cost	(50)*(51)	0.2
forklift cost	(52)*(53)	11.2
kiln labor	[(54)*(55)*(66)]/(65)	
kiln maintenance	(56)/(12)	
office overhead	(57)/(12)	
energy cost	[(58)*(59)+(60)*(61)]/(12)	
interest on inventory	[(62)*(64)*(13)]/(12)	1.14E-04
degrade	(62)*(63)	3.57E-05
	TOTAL ($)	525.69
	Cost per day	**$1.44**

Table 30: Cost of Treating with Biocide and Air Drying pallets

	Poplar	Oak
Air Dry Cost per Day	1.44	1.44
Days to Dry	6	29
Total Air Dry Pallet Cost	8.64	41.76
Price Per Pallet	0.43	2.08
Chemical Cost per pallet	0.40	0.40
Price Per Pallet with Chemicals	0.83	2.48

4.4 Summary

This study demonstrated that all four methods tested prevented mold growth on yellow-poplar and oak pallets. Since the effectiveness was equal for all methods, the most important comparisons to be made are based on cost and drying times. The estimated drying times for drying poplar pallets on the air dry yard, fan shed, and in the kiln can be seen in Figure 30.

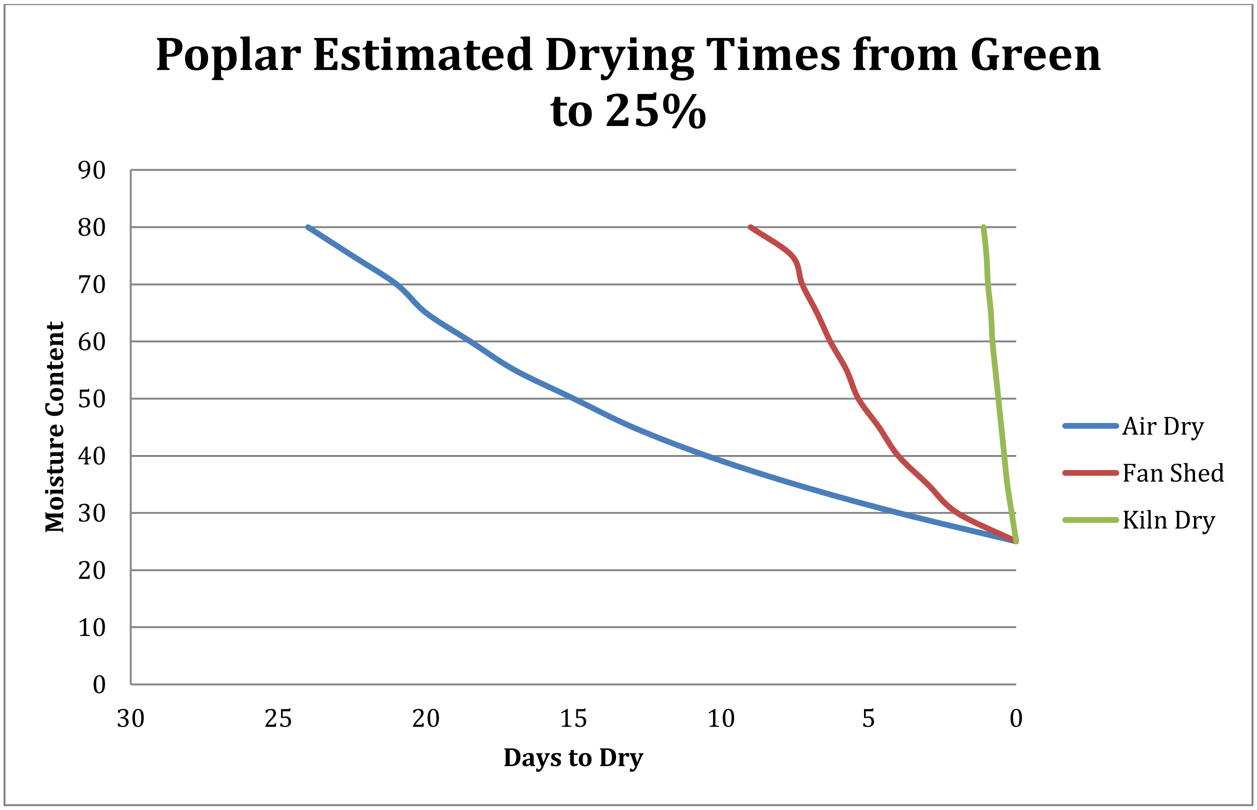

Figure 30: Poplar Estimated Drying Times for All Drying Methods

The estimated drying times for oak pallets for all drying methods can be seen in Figure 31.

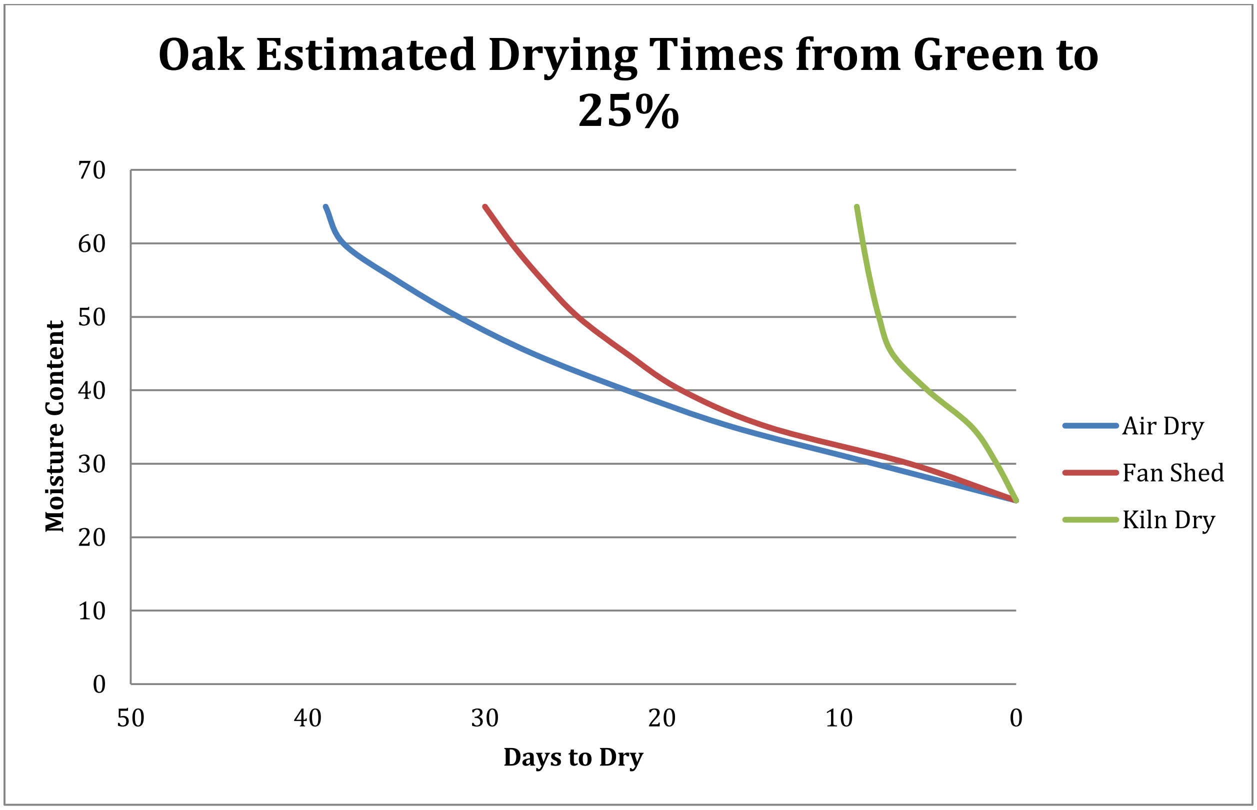

Figure 31: Oak Estimated Drying Times for All Drying Methods

Figure 31 compares each of the drying methods based on drying time, the percentage moisture content loss per day, and the calculated cost per day for each species of pallet tested. The values found in Table 31 are the actual cost that occurred during this testing. The values found in Table 32 are values that have been adjusted to calculate the cost to dry from green down to 25% moisture content. These values were derived from data obtained from actual drying of pallets.

Table 31: Detailed Summary of Actual Drying Methods Costs

		Days to Dry	Initial MC	Final MC	MC Loss/day	Cost per day	Total Cost	Per pallet
Air Dry	Oak	20	38.80%	25.5%	0.67%	1.43	28.60	1.43
	Poplar	17	49.80%	25.3%	1.44%	1.43	24.31	1.22
Fan Shed	Oak	16	36.90%	25.0%	0.74%	1.60	25.60	1.28
	Poplar	0	21.60%	21.6%	0.00%	1.60	0.00	0.00
Kiln Dry	Oak	8	47.90%	23.2%	3.09%	29.08	232.64	11.63
	Poplar	4	39.10%	14.3%	6.20%	29.08	116.32	5.82
Chem Air Dry	Oak	29	45.10%	25.0%	0.69%	1.65	51.85	2.59
	Poplar	6	57.70%	25.0%	5.45%	1.65	13.90	0.70

Table 32: Detailed Summary of Estimated Drying Cost from Green to 25% Moisture Content

		Days to Dry*	Initial MC	Final MC	MC Loss/day	Cost per day	Total Cost	Per pallet
Air Dry	Oak	39	64.0%	25.0%	1.00%	1.43	55.77	2.79
	Poplar	24	83.0%	25.0%	2.42%	1.43	34.32	1.72
Fan Shed	Oak	30	64.0%	25.0%	1.30%	1.60	48.00	2.40
	Poplar	9	83.0%	25.0%	6.44%	1.60	14.40	0.72
Kiln Dry	Oak	9.5	64.0%	25.0%	4.11%	29.08	276.26	13.81
	Poplar	3	83.0%	25.0%	19.33%	29.08	87.24	4.36
Chem Air Dry	Oak	39	64.0%	25.0%	1.00%	1.65	68.35	3.42
	Poplar	24	83.0%	25.0%	2.42%	1.65	43.60	2.18

*These values are based on Estimated Drying Values derived from actual data

The drying times that were estimated based on actual drying data obtained during this study can be seen in Figure 32 and Figure 33. These graphs can be used to determine the amount of time required to dry pallets down to 25% moisture content. Using the gridlines on the graphs, the total drying time can be estimated based on the initial moisture content of the pallets.

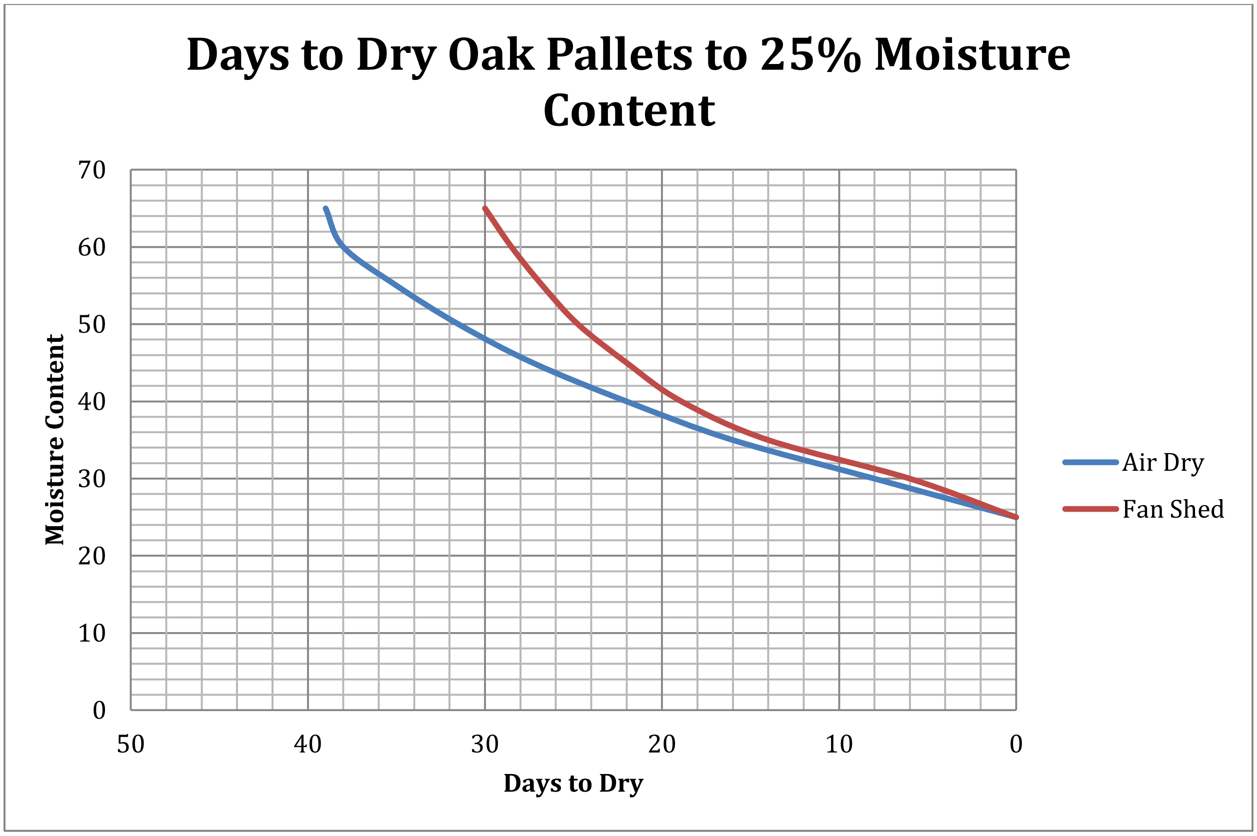

Figure 32: Drying Time Estimates for Oak Pallets Based on Initial Moisture Content

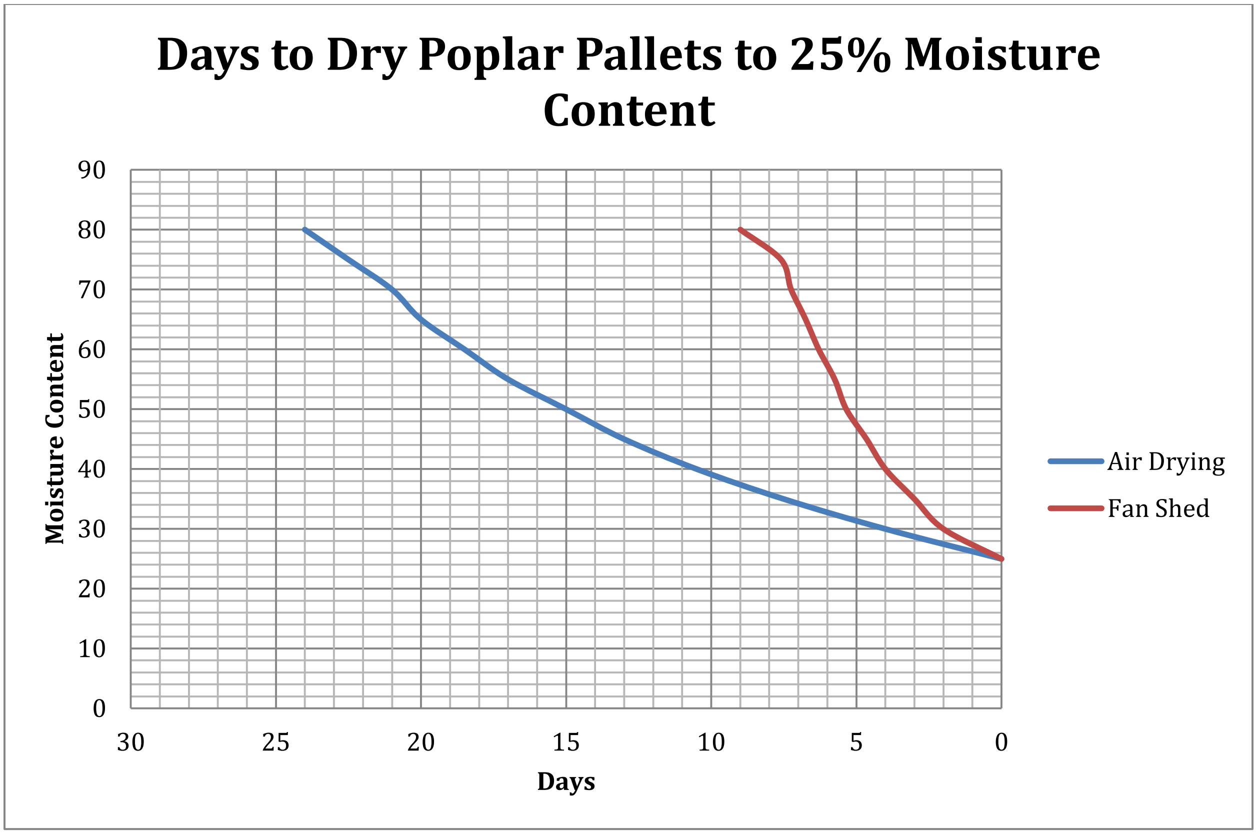

Figure 33: Drying Time Estimates for Poplar Pallets Based on Initial Moisture Content

In addition to determining drying times down to 25% moisture content, the drying curves to estimate the drying time down to 19% moisture content can be seen below in Table 33 and Figure 34 and Figure 35. These graphs are from actual data and times but plotted separately from the 25% moisture content graphs to simplify the drying time estimation based on initial moisture content.

Table 33: Days Required to Dry Pallets to 19% Moisture Content

Days to Dry Pallets to 19% MC				
	Air Dry		Fan Shed	
Initial MC	**Poplar**	**Oak**	**Poplar**	**Oak**
80	31	-	12	-
75	29.5	-	10.6	-
70	28	-	10.25	-
65	27	46	9.75	35
60	25.5	45	9.3	34
55	24	42	8.75	32
50	22	38.5	8.35	30
45	20	34.3	7.65	27
40	17.5	29	7	24
35	14.5	23	6	19
30	11	15	5	11
25	7	7	3	5
19	0	0	0	0

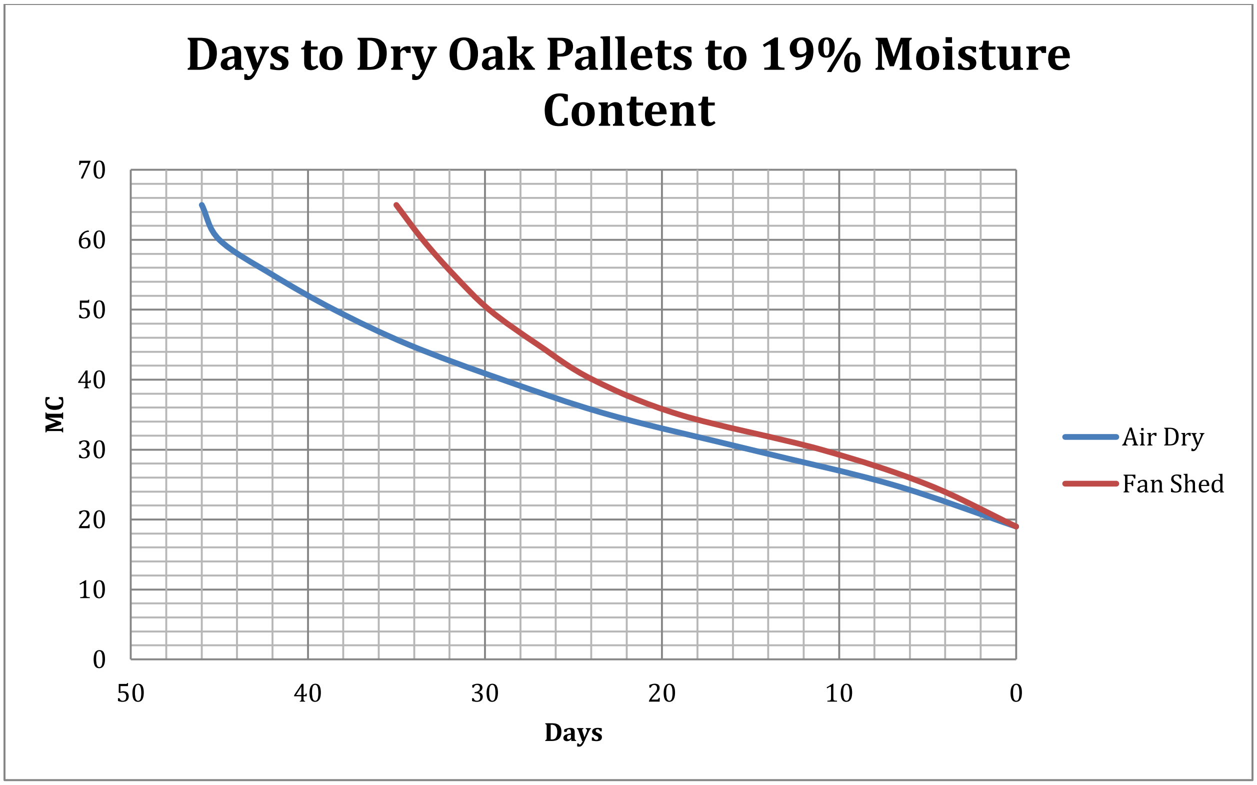

Figure 34: Days Required to Dry Oak Pallets to 19% Moisture Content

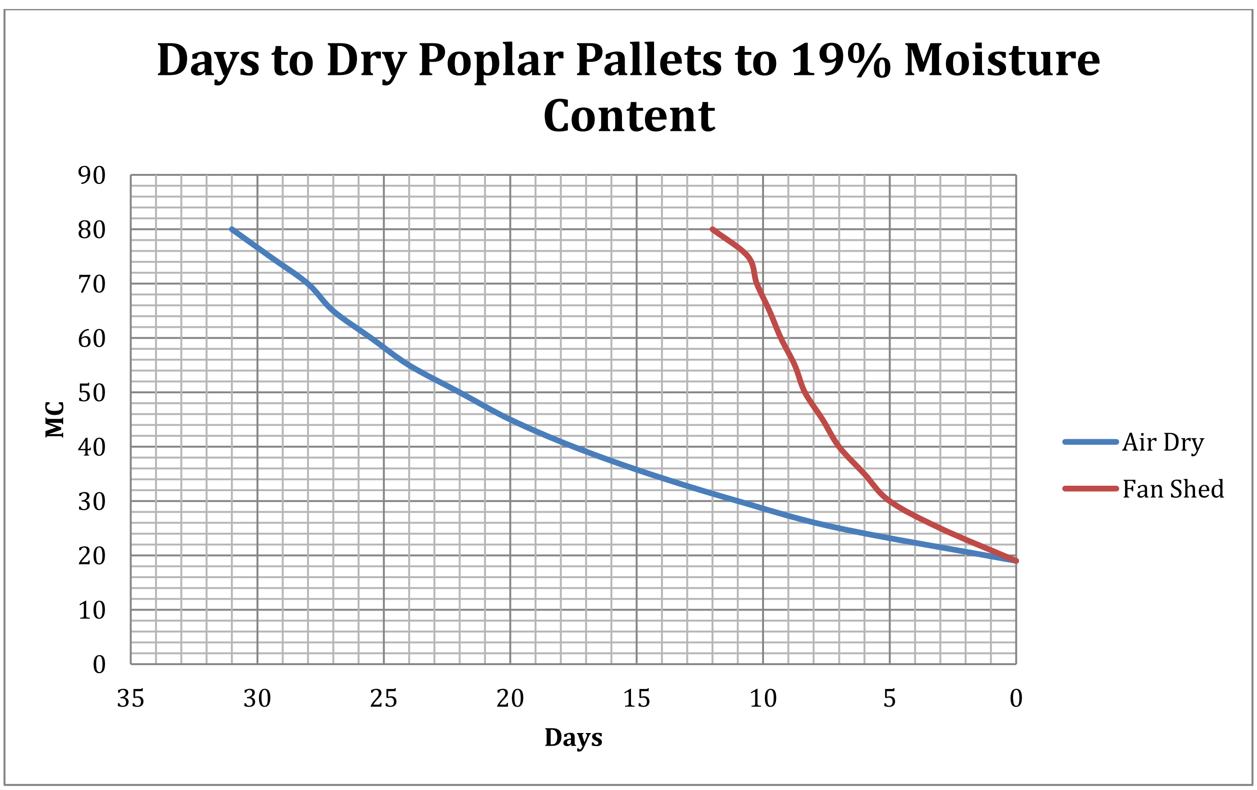

Figure 35: Days Required to Dry Poplar Pallets to 19% Moisture Content

4.4.1 Air drying

Based on the drying cost calculations, air drying has the lowest cost per day by means of treating pallets for mold protection. However, since this can take up to 39 days, this is not always the cheapest means of drying pallets down to 25% moisture content. This drying rate heavily depends on initial moisture content and drying conditions. As the drying rates vary depending upon the weather conditions, the drying costs also vary because of the amount of time it takes to dry. This change in time increases the amount of inventory costs. Paying tax and land values for 30 days is going to be less expensive than paying them for 50 days.

4.4.2 Fan Shed

The fan sheds provided a consistent drying rate, while protecting the pallets from rain. Since the fan sheds have a roof system that protects them from the weather and direct sunlight, the entire stack of pallets dries more uniformly than air dried pallets. While this method produces daily cost of operation of $1.60 which is 11% more than air drying, fan shed drying can dry oak pallets 2.6 times faster and poplar pallets 1.3 times faster than air drying them. In the end, fan shed drying can be the cheapest means of drying pallets as shown by the data presented in Table 32 shows that it takes 30 days to dry oak pallets from 64% to 25% at a cost of 1.60 per day for 20 pallets, which yields a per pallet cost of $2.40. Looking at the same table, it takes 9 days to dry poplar pallets from 83% to 25% at a cost of 1.60 per day for 20 pallets, which yields a per pallet cost of $0.72.

4.4.3 Kiln Drying

The kiln schedules that were developed allow pallets to be kiln dried at rates which are optimal for pallets. Although the cost of operating a dry kiln is 18 times the cost of fan shed drying and 20.3 times the cost air drying pallets, pallets can be dried at a rapid drying rate without causing excessive degrade. Kiln drying pallets is much faster than air drying or fan shed drying pallets. Oak pallets can be kiln dried 4.1 times faster and poplar pallets can be kiln dried

8 times faster than air drying. Oak pallets can be kiln dried 3.2 times faster and poplar pallets can be kiln dried 3 times faster than drying in a fan shed. Kiln drying pallets is the most expensive out of the methods tested, but has the ability to dry pallets down to 25% moisture content without significant degrade. Due to this rapid drying rate, the pallets have lower inventory cost through the process than pallets sitting on the air dry yard. Kiln drying pallets also allows for a more uniform drying rate that is easily repeated yielding to more uniform pallets supplied at a consistent rate throughout the year.

4.4.4 Chemical Treatment

The chemical treated pallets have the same cost as the air dried pallets, with the additional cost of the chemicals. Out of all of the pallets tested, the chemically treated pallets stick out as a better looking pallet. The brightener that was in the solution kept the pallets from turning dark in color from the sun, and it controlled the mold growth on the pallets.

4.4.5 Cost Estimation and Net Present Value

While the costs discussed are limited on the sample size of the pallets tested, the methodology used to calculate these cost can be used by any pallet manufacturer to more accurately predict their costs based on the operations size and local expenses. The cost estimation process that manufacturers can follow to accurately calculate the cost of drying pallets at their facility can be calculated by using the methods described in section 4.3. Cost Estimation. The manufacturer will easily be able to calculate cost by inputting as much data into the analysis, then using the formulas found in Table 18, the inputs can be transformed into cost.

Often when comparing the costs versus revenues generated by different processes a Net Present Value (NPV) cost comparison is useful. A net present value analysis compares the present value of money today to the present value of money in future, taking inflation and returns into account. A Net Present Value (NPV) cost comparison was conducted on air drying, fan shed drying, and kiln drying to determine which drying method produced more revenue over a period of three years (36 months). The values for this NPV calculation can be seen in Table 34. Looking at the NPV values on the bottom line, the fan shed yields the highest revenue generation over a 3 year period, therefore making it the most lucrative method of the three.

Table 34: Net Present Value Cost Comparison

	Air Dry	Fan Shed	Kiln
Purchase of equipment (PE)	0	950	10,000
Installation and interfacing (IF)	0	150	1,500
Plant layout modification (PL)	0	0	0
Product Redesign (PR)	0	0	0
Hiring of skilled workers (SK)	0	0	0
Retraining of workers (RT)	0	0	0
Periodic Costs for each period (t)			
Skilled labor costs (SL)	50	50	100
Energy cost for machines (EM)	0	40	200
Extra plant utility costs (PU),	0	0	0
Additional service costs (AS)	0	0	0
Maintenience costs (MC)	0	0	100
Periodic Benefits for each period (t)			
Revenue for increased output (RO)	200	300	800
Savings from reduced labor (RL)	0	0	0
Savings from reduced inventories (RI)	0	0	0
Material savings(MS)	0	0	0
Savings in warranty related costs (WR)	0	0	0
Revenue from Better Market Position (MP)	0	0	0
Initial and Periodic Tax Effects			
Investment tax credit (IT,t=0)	0	0	0
Depreciation Tax Shields (DT,t)	0	0	0
Taxes on net change in operating cashflows (TC, t)	0	0	0
SUMMARY			
Initial acquisition costs at t=0	0	1,100	11,500
Periodic cost	50	90	400
Periodic benefits	200	300	800
Interes rate	0.67%	0.67%	0.67%
Number of periods	36	36	36
NPV	**4,786.77**	**5,601.48**	**1,264.72**

4.5 Heat Treatment and Mold Prevention Schedules

The second objective of this work was to develop a heat treating and drying schedule that would meet the IPPL-#15 requirements and prevent mold growth; therefore, two heat treatment and drying tests were conducted for each species of wood tested, for a total of four tests. Each species of pallet had two tests that consisted of two different sets of conditions to determine which produced the least amount of defects. The pallets were first heated in the dry kiln until the core temperature of the pallet stringer reached 133°F for at least 30 minutes. After the pallets had reached the 133°F mark for 30 minutes, the kiln settings were adjusted to dry the pallets.

The pallets were inspected both before and after the heat treatment test to determine the amount of drying degrade that was caused by the heat treatment process. The splits were marked before the testing with a Sharpie® marker. After the test, the number of splits that occurred during the heat treatment process were easily visible. The splits that did not have any Sharpie® marker on them were caused by the heat treatment process. The pallets that were heat treated were only considered to be degraded based on the PDS Pallet Component Grades Lumber Characteristic Restrictions that can be found in Appendix D. Of the restrictions, the only thing that can be changed by drying and cause pallet degrade within the pallet are the splits at the fasteners and the stringers.

4.5.1 Oak Pallets

Test 1:

For test 1, the dry bulb temperature was set at 180°F. 180°F was used as a starting point for the heat treatment schedule because in order to get the core of the pallets to reach 133°F in a short amount of time, the temperature inside the kiln must be much higher. The wet bulb temperature was set at 175°F to ensure that the vents did not open during the heating of the kiln.

The steam spray was turned off, allowing the moisture escaping the pallets to increase the relative humidity inside the kiln. These settings on the kiln produced a maximum relative humidity of 89%. The pallet stringers had an average initial moisture content of 49.2% that was measured using the oven dry method. Two thermocouple sensors were pushed into small drilled holes and a wooden toothpick was inserted in the hole to hold the wire, and to block the hot air from contacting the sensor. Figure 36 shows the internal temperature of the pallets throughout the heat treating cycle.

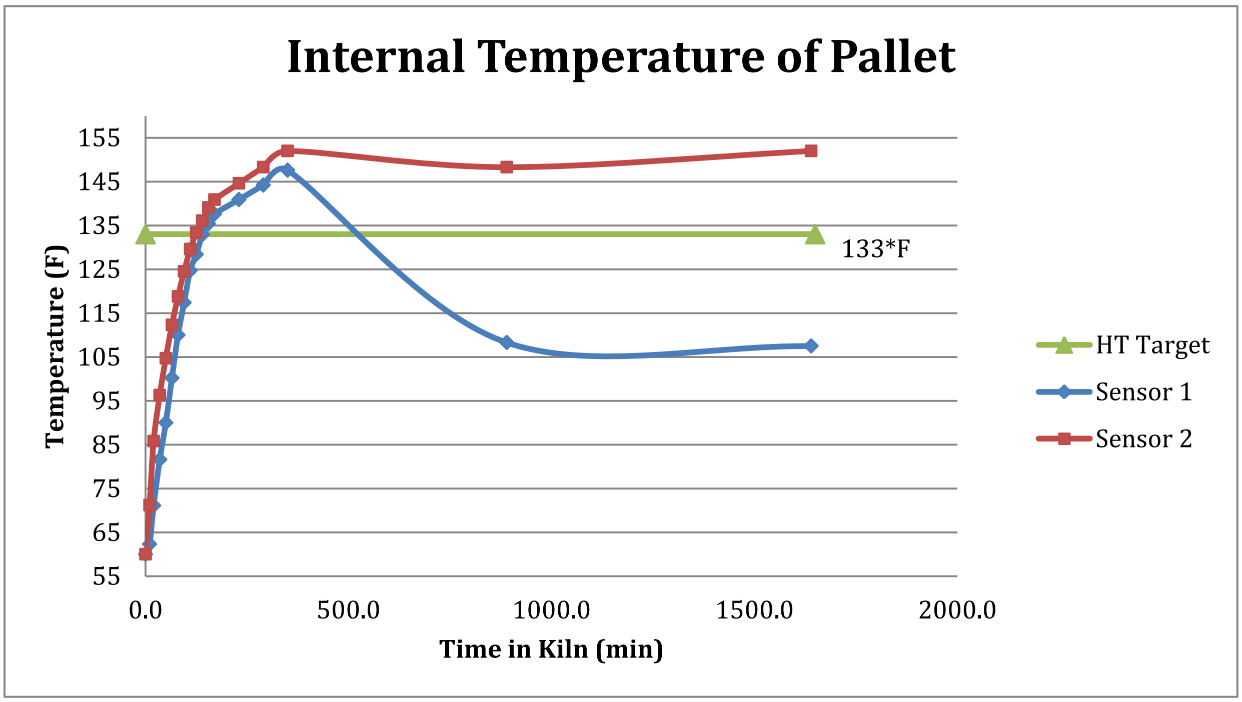

Figure 36: Oak Internal Pallet Temperature during Heat Treatment Cycle Test 1

After the pallets had reached the required 133° for 33 minutes, the kiln controls were cut back to 130°F dry bulb temperature and 121°F wet bulb temperature (12.7% EMC) to open the vents to reduce the humidity inside the kiln and to lower the temperature inside the kiln. After allowing the humidity and heat to escape the kiln, the kiln controls were lowered to 110°F dry bulb and 98°F wet bulb temperature (10.8% EMC) to dry the pallets after the heat treatment process. The pallets were heat treated and dried from 49.2% moisture content to 23.4% moisture content in 60 hours with 0% degrade in the pallets. The kiln conditions during the oak heat treatment and drying test can be seen in Figure 37.

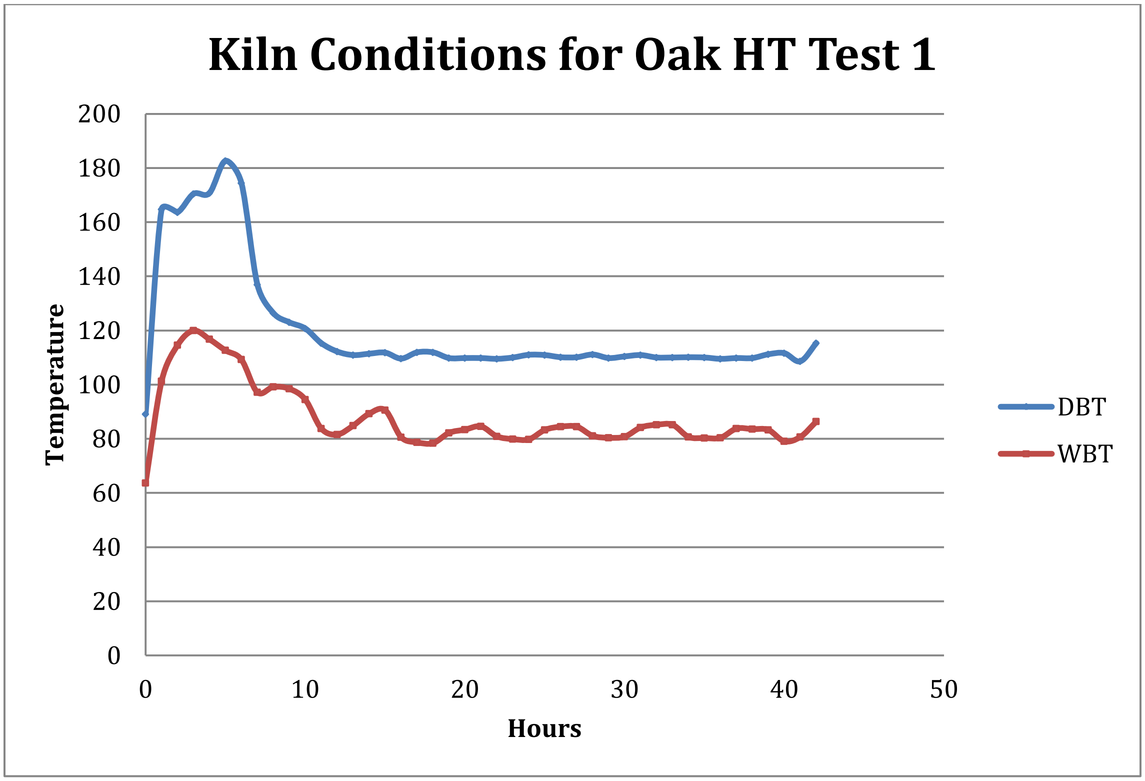

Figure 37: Kiln Conditions for Oak Heat Treatment and Drying Test 1

The pallets that were treated during this first test showed no signs of splits caused by the heat treatment and following drying. The splits that were marked before testing had not gotten any larger due to the drying, and there were no new splits that were caused by the drying process.

Test 2:

Since the first test seemed conservative, a second test was conducted at a slightly higher temperature to accelerate the process. The schedule that was used for this test can be seen in Table 35.

Table 35: Oak HT Drying Schedule

Oak HT Drying Schedule		
	Dry Bulb	**Wet Bulb**
Initial	190	185
> 35%	160	145
35 to 25	130	90

For test 2, the dry bulb temperature was set at 190°F and a wet bulb of 185°F was set on the kiln which wouldn't allow the vents to open unless the relative humidity exceeded 90%. The steam spray was turned off, allowing the moisture escaping the pallets to increase the relative humidity inside the kiln creating a relative humidity of 28%. The pallet stringers had an average initial moisture content of 55.6% that was measured using the oven dry method. Figure 38 shows the internal temperature of the pallets throughout the heat treating cycle.

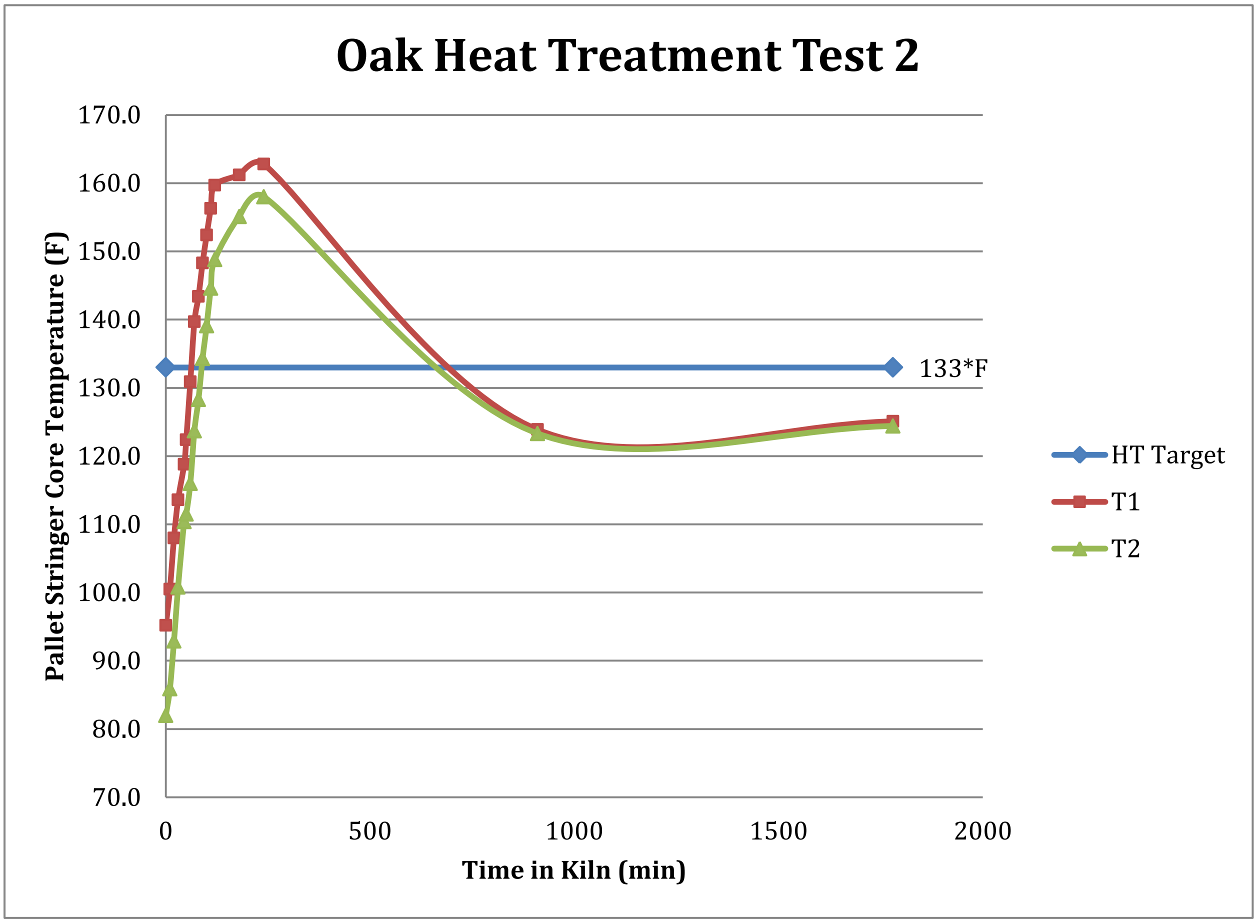

Figure 38: Oak Internal Pallet Temperature during Heat Treatment Cycle Test 2

After the pallets had reached the required 133° for 33 minutes, the kiln controls were cut back to 160°F dry bulb temperature and 145°F wet bulb temperature to open the vents to reduce the humidity inside the kiln and to lower the temperature inside the kiln. After allowing the humidity and heat to escape the kiln, the kiln controls were lowered to 130°F dry bulb and 90°F wet bulb temperatures to dry the pallets after the heat treatment process. The kiln conditions for the oak heat treatment and drying schedule test 2 can be seen in Table 30.

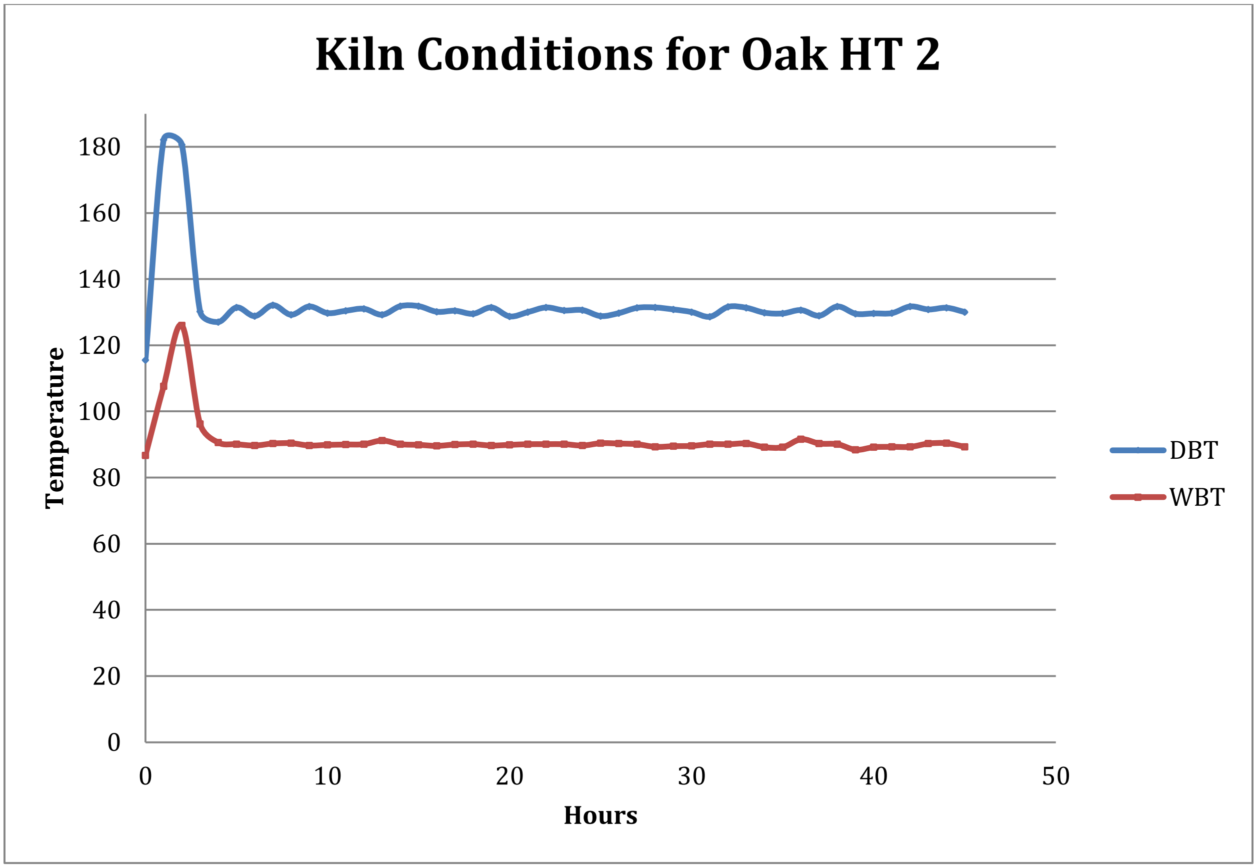

Figure 39: Kiln Conditions for Oak Heat Treatment and Drying Schedule 2

Again, the splits that were present before the heat treatment process were marked with a Sharpie® marker to determine if the splits got any larger, or any new splits appeared after the heat treatment process. The splits that occurred during the heat treatment and drying schedule can be seen in Table 36. According to the NWPCA part grades, none of the pallets had enough splits that were severe enough to degrade the pallet. The pallets were heat treated and dried from 55.6% moisture content to 24.9% moisture content in 41 hours and there were no signs of degrade in the pallets, based on the NWPCA part grade restrictions.

Table 36: Splits That Occurred During Oak HT Test 2

Pallet	Splits
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	1
10	2
11	1
12	0
13	0
14	1
15	0
16	0
17	0
18	0
19	0
20	1

In both of the oak tests, there was some slight warp that occurred on the top two pallets, but according to the NWPCA pallet component grades lumber characteristic restrictions, there is not a limitation on warp. The pallet with the most severe warp, when placed on a flat surface, had one corner that was approximately 3/8" out of plane. Once this pallet was inspected, and other pallets were placed on top of the warped pallet, the warp was almost eliminated, therefore the warp only occurred on the top 2 pallets when they were not loaded. Once they were loaded, the warp was no longer visible, making the warp negligible.

4.5.2 Poplar Pallets

Test 1:

For test 1, the dry bulb temperature was set at 180°F. 180°F was used as a starting point for the heat treatment schedule because in order to get the core of the pallets to reach 133°F in a short amount of time, the temperature inside the kiln must be much higher. The wet bulb temperature was set at 175°F to ensure that the vents did not open during the heating of the kiln. The steam spray was turned off, allowing the moisture escaping the pallets to increase the relative humidity inside the kiln. These settings on the kiln produced a maximum relative humidity of 89%. The pallet stringers had an average initial moisture content of 49.2% that was measured using the oven dry method. The internal core temperature for the poplar pallet test one can be seen in Figure 40.

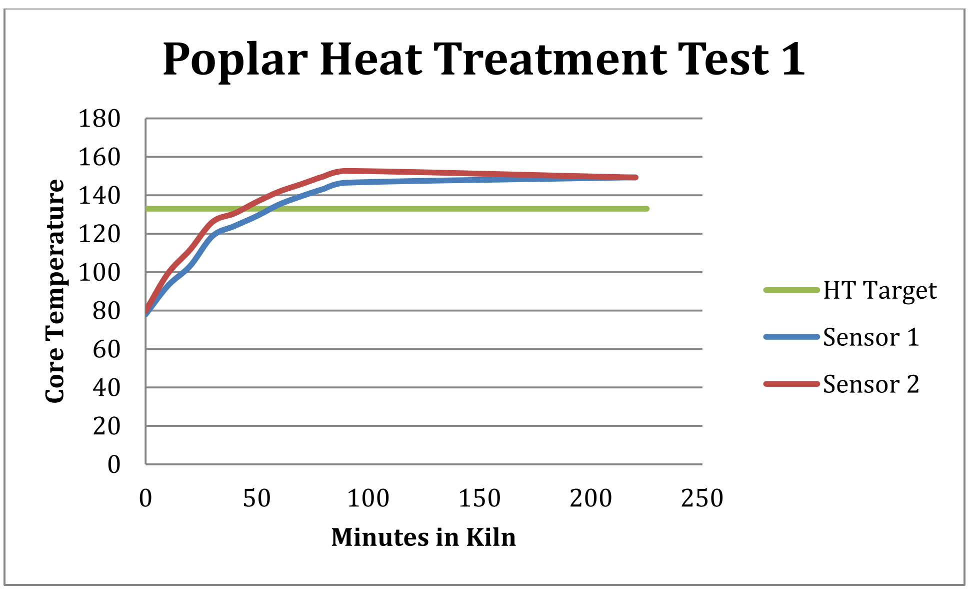

Figure 40: Poplar Internal Pallet Temperature during Heat Treatment Test 1

After the pallets had reached the required 133° for 33 minutes, the kiln controls were cut back to 160°F dry bulb temperature and 136°F wet bulb temperature (7.0% EMC) to open the vents to reduce the humidity and temperature inside the kiln. After allowing the humidity and heat to escape the kiln, the kiln controls were set to 165°F dry bulb and 120°F wet bulb temperature (3.2% EMC) to dry the pallets after the heat treatment process. The kiln conditions for the first poplar heat treatment and drying schedule can be seen Figure 41

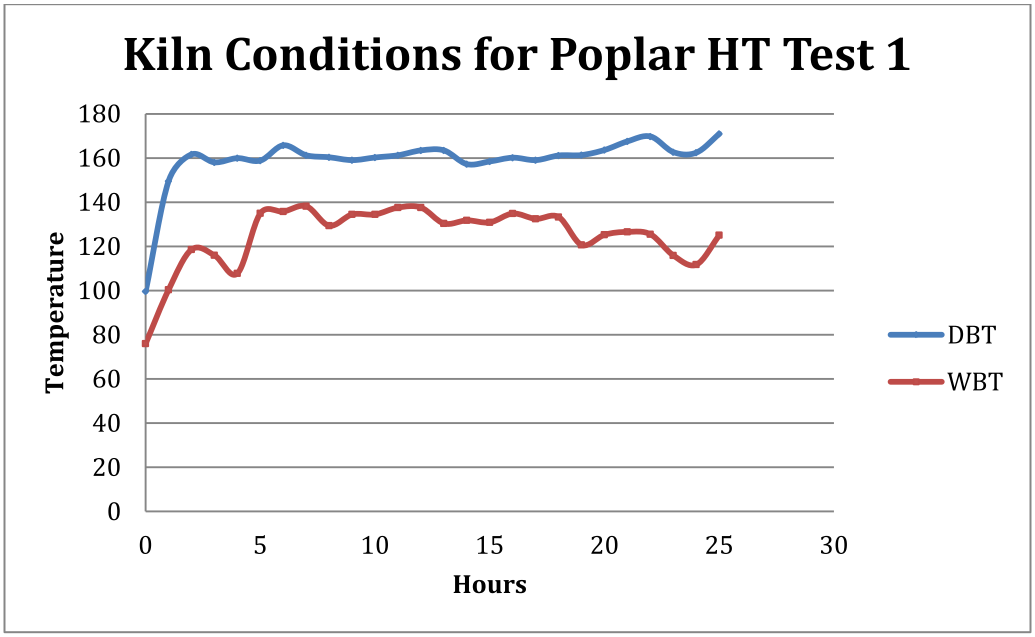

Figure 41: Kiln Conditions for Poplar Heat Treatment and Drying Schedule 1

The pallets that were treated during this first test showed no signs of splits caused by the heat treatment and drying schedule. The splits that were marked before testing had not gotten any larger due to the drying, and there were no new splits that were caused by the drying process. The pallets were heat treated and dried from 43.8% moisture content to 23.5% moisture content in 17 hours with 0% degrade in the pallets according to the NWPCA pallet component grades.

Test 2:

The first test seemed conservative; Therefore, a second test was conducted at a higher temperature to accelerate the process. The heat treatment drying schedule that was used for this second poplar test can be seen in Table 37.

Table 37: Poplar HT Drying Schedule

Poplar HT Drying Schedule		
	Dry Bulb	**Wet Bulb**
Initial	190	185
> 40%	155	126
40 to 25	165	120

For test 2, the dry bulb temperature was set at 190°F and a wet bulb of 185°F was set on the kiln which wouldn't allow the vents to open unless the relative humidity exceeded 90%. The steam spray was turned off, allowing the moisture escaping the pallets to increase the relative humidity inside the kiln creating a relative humidity of 26%. The pallet stringers had an average initial moisture content of 42.1% that was measured using the oven dry method. Figure 42 shows the internal temperature of the pallets throughout the heat treating cycle.

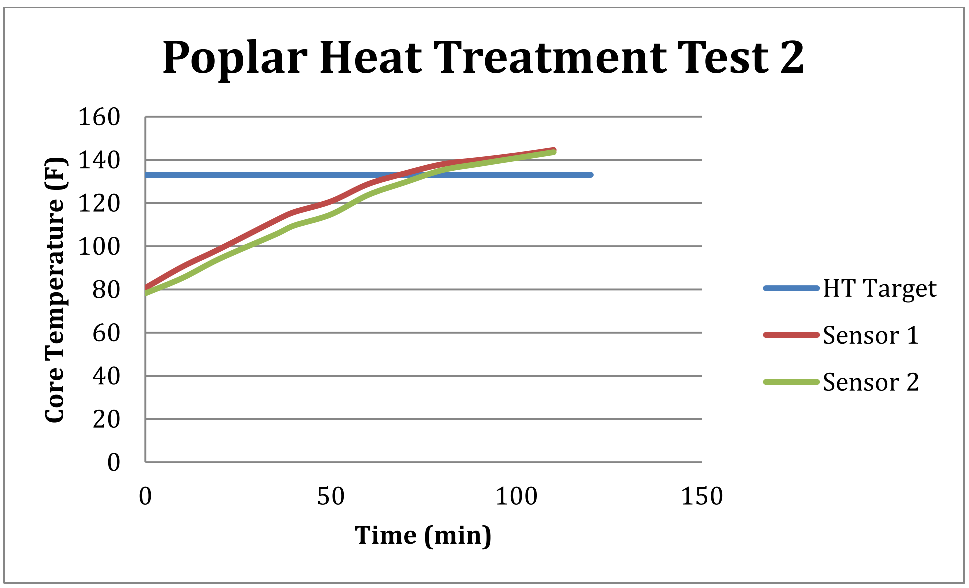

Figure 42: Poplar Internal Pallet Temperature during Heat Treatment Test 2

After the pallets had reached the required 133° for 33 minutes, the kiln controls were cut back to 155°F dry bulb temperature and 126°F wet bulb temperature (6.0% EMC)to open the vents to reduce the humidity inside the kiln and to lower the temperature inside the kiln. After allowing the humidity and heat to escape the kiln, the kiln controls were changed to 165°F dry bulb and 120°F (3.2% EMC) wet bulb temperatures to dry the pallets after the heat treatment process. The kiln conditions for the second poplar heat treatment and drying schedule can be seen in Figure 43.

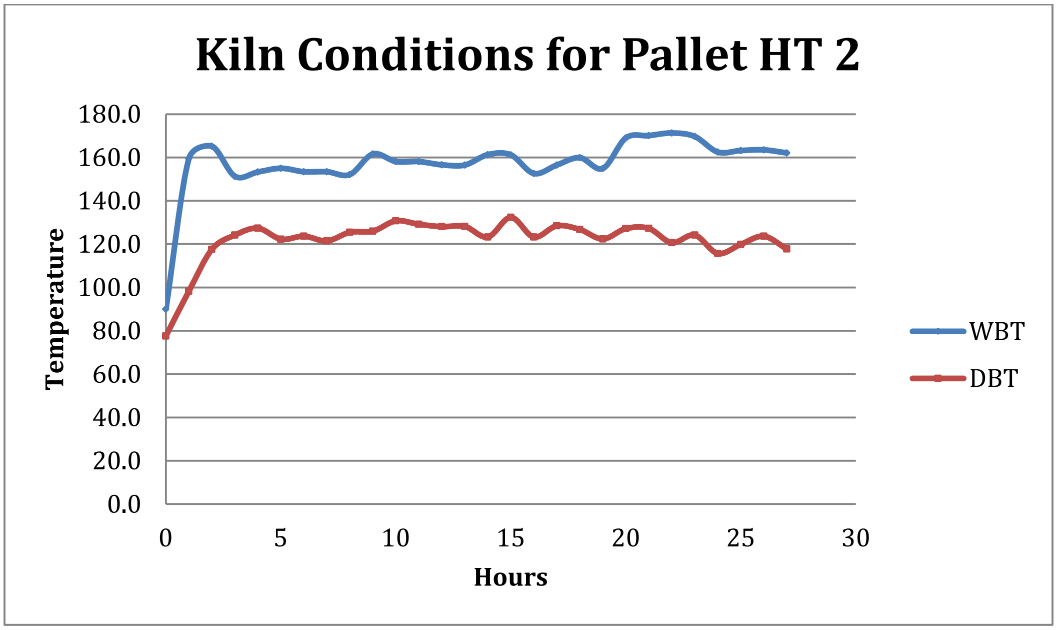

Figure 43: Kiln Conditions for Poplar Heat Treatment and Drying Schedule 2

Again, the splits that were present before the heat treatment process were marked with a Sharpie® marker to determine if the splits got any larger, or any new splits appeared after the heat treatment process. The splits that occurred during this last poplar heat treatment and drying schedule can be seen in Table 38. According to the NWPCA part grades, none of the pallets had enough drying damages that were severe enough to degrade the pallet. The pallets were heat treated and dried from 42.1% moisture content to 23.5% moisture content in 16 hours and there was no degrade in the pallets that would require downgrading the pallet, based on the NWPCA part grade restrictions.

Table 38: Splits that occurred during Poplar Heat Treatment and Drying Schedule 2

Pallet	Splits
1	0
2	0
3	1
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	1
13	0
14	0
15	0
16	0
17	0
18	1
19	1
20	0

Chapter 5: Summary & Conclusions

5.1 Summary

A pallet is a portable, horizontal, rigid platform used as a base for assembling, storing, stacking, handling, and transporting shipping containers as a unit load (Twede and Selke, 2005). Pallets are vital for commerce since the majority of consumer goods that are transported; including foods, metals, paper and printing, and chemicals are moved on pallets. There are between 1.9 and 2.0 billion pallets in use each day (White, 2004). The wooden pallet and container industry is an important component of the hardwood lumber manufacturing industry since approximately 25% of all hardwood lumber is consumed in the manufacture of pallets. Wood makes up the vast majority of pallets because they are reusable, recyclable, repairable, and are made from a renewable resource.

A major issue facing the wooden pallet and container industry is the potential for mold growth on the wood. Mold on pallets can discolor and contaminate products, contaminate the workplace which can be a human health hazard, and present bad visual aesthetics. Due to the importance of the wood pallet industry on national commerce, and the health of the hardwood industry, it is vital that cost effective mold prevention methods be provided to the industry. Currently there is limited information regarding the effectiveness and cost of different mold prevention methods. The goal of this work was to make this information available to pallet manufacturers. The specific objectives of this project were:

1. To evaluate and compare the effectiveness and cost of the following existing mold strategies for hardwood pallets: air drying, forced air drying (fan shed), kiln drying, and chemical treatment, and
2. Develop and evaluate a procedure for preventing and controlling mold growth on heat treated hardwood pallets

To evaluate and compare methodologies and costs of the most common mold prevention strategies for hardwood pallets, tests were conducted on green manufactured yellow-poplar and oak pallets. Green pallets were dried to a moisture content of 25% by air-drying, chemical treatment followed by air-drying, forced air drying and kiln drying. The time to reach the target moisture content was recorded in addition to climatic variables. Costs for each treatment method were collected and used for comparison of each method. After the pallets were dried, they were exposed to mold spores and placed into a chamber for fourteen days. The pallets were then inspected and evaluated for mold growth. The second phase of this research was to develop a HT/kiln dry schedule that will both meet IPPC-ISPM #15 heat treatment requirements and achieve the desired 25% moisture content with minimal degrade.

5.2 Conclusions

In regards to the first objective the following conclusions were determined:

- It was demonstrated during the weather conditions during testing, that when pallets dried to an average of 19% moisture content[3] are exposed to mold spores (Aspergillus, Stachybotrys, and Penicillium) and placed in a closed environment for a period of 14 days, no mold will grow.
- Air-drying pallets, chemical application in conjunction with air-drying pallets, fan shed drying pallets and kiln drying pallets to a 19-24% moisture content has been demonstrated to prevent mold growth on oak and yellow poplar pallets.
- Estimates for the time required to dry yellow-poplar and oak pallets to 19% and 25% moisture content were developed for air-drying, forced air-drying and kiln drying as presented in Table 39.

[3] Average moisture content of the pallet, measured by oven-dry method of pallet stringer samples in this study.

Table 39: Number of Days to Dry Pallets to 25% Moisture Content Based on Actual Drying Times

Days to Dry Pallets to 25% MC				
	Air Dry		Fan Shed	
Initial MC	**Poplar**	**Oak**	**Poplar**	**Oak**
80	24	-	9	-
75	22.5	-	7.6	-
70	21	-	7.25	-
65	20	39	6.75	30
60	18.5	38	6.3	28.5
55	17	35	5.75	26.75
50	15	31.5	5.35	24.75
45	13	27.3	4.65	22.0
40	10.5	22	4	18.9
35	7.5	16	3	14.0
30	4	8	2	6
25	0	0	0	0.0

- Estimates of the cost drying oak and yellow poplar were determined for air-drying, forced air-drying, kiln drying and chemical treatment of pallets. The relative differences are presented in the results section 4.4 and also in Table 40.

		Kiln Drying versus other Methods	
		Oak	**Poplar**
Air Dry	Time	4.1x faster	3.2x faster
	Cost	20.3x faster	
Fan Shed	Time	3.2x faster	3x faster
	Cost	18x cost	

Table 40: Relative Differences in Drying Methods from Green to 25% Moisture Content

- A methodology for determining more precise costs based on a particular operations size and local costs was also presented so that manufacture's can develop more accurate costs for the size of their operations.
- It was determined that air drying had the lowest daily operational cost but not the lowest total drying cost.
- Fan shed drying had the lowest drying cost to achieve 25% moisture content.

- Kiln drying was the most expensive daily and total cost, but was the fastest method.
- A Net Present Value analysis showed that over a 3 year (36 month) time period, fan shed drying provide the greatest revenue generation method for drying pallets based on the values used in this study.

In regards to the second objective the following summary is provided:

- Two heat treating and drying schedules were developed to both meet IPPC-ISPM #15 requirements and achieve the desired 25% moisture content with minimal degrade. This was accomplished by testing several HT/drying schedules on green yellow-poplar and oak pallets until the pallets met the criteria for being heat treated and had minimal degrade.
- An oak schedule was developed by modifying a T4-C2 kiln schedule that would meet IPPC-ISPM #15 heat treatment standards and kiln dry pallets that were originally 55% moisture content to 25% moisture content in 30 hours.
- A yellow poplar schedule was developed by modifying a T11-D4 schedule that would meet IPPC-ISPM #15 heat treatment standards and dry pallets that were originally at 50% moisture content to 25% in 16 hours.

5.3 Limitations:

- Since there are many factors in air drying and forced air drying wood, such as temperature, relative humidity, and air velocity, it should be known that these results are for the specific conditions during each test and should be used as an estimate, and not exact figures. While no mold grew on the air drying, fan shed, and kiln dried pallets during the drying process it is possible that under different conditions it might. Also, the drying costs presented were derived for the experimental conditions and would likely be lower due to economics of scale. However, we do feel that they represent the relative differences between each treatment method. More precise estimates can be derived using the methods outlined in this work. The data presented for estimations was based on a small sample size (approximately 20 pallets per sample) and the drying times from green were often estimated rather than measured experimentally.

5.4 Future Work

To improve upon the accuracy of this work, future work should include multiple repetitions of each drying method and species. Also, while it is difficult to obtain pallets with a moisture content that represents the average high green moisture content, using such pallets would likely increase the accuracy of the drying rates. Ideally, the final mold test for the different treatments should include a control, or a trailer inoculated with mold on green pallets. Finally, a comparison of the small scale tests to actual industrial size testing would allow for any scaling differences to be addressed.

Appendix:

Appendix A: Pallet Species Classes (ANSI 2005)

Pallet Component Wood Species Classes*

CLASS 1
Hickory
Birch:
- Yellow
- Sweet

Maple:
- Sugar
- Black
- Red

Ash:
- Green
- White

Elm:
- Rock
- Slippery

American Beech
Black Locust
Black Cherry
Tanoak
Dogwood
Persimmon
Eucalyptus

CLASS 2
Bigleaf Maple
Oregon Ash

CLASS 3
Sweetgum
Tupelo
Paper Birch
Ash:
- Black
- Pumpkin

Hackberry
Sycamore
Maple:
- Silver
- Striped

Magnolia

CLASS 4
Oregon White Oak
California Black Oak
Cascara
Chinquapin
Myrtle
Pacific:
- Madrone

CLASS 6
Red Alder

CLASS 7
Aspen:
- Bigtooth
- Quaking

Catalpa
Buckeye
Butternut
American Basswood
Cottonwood:
- Black
- Balsam Poplar
- Eastern

CLASS 11
Douglas-Fir:
- Coast
- Interior West
- Interior North
- Interior South
- Western Larch

CLASS 12
Hemlock:
- Western
- Mountain

Fir:
- California Red
- Grand
- Noble
- Pacific Silver
- White

CLASS 13
Spruce:
- White
- Black
- Red
- Engelmann
- Sitka

Pine:
- Sugar
- Western White
- Lodgepole
- Ponderosa
- Monterey
- Jack
- Norway
- Eastern White

Southern Pine:
- Pitch
- Pond
- Spruce
- Virginia

Fir:
- Subalpine
- Balsam

Baldcypress
Eastern Hemlock
Western Red Cedar
Redwood

CLASS 14
Cedar:
- Alaska
- Incense
- Port Orfod
- Atlantic White
- Northern White
- Eastern Red

CLASS 21
Eastern Red and White Oaks

CLASS 22
Southern Pine
- Loblolly
- Longleaf
- Shortleaf
- Slash

CLASS 29
Yellow-Poplar

SOUTHERN ASIAN SPECIES

CLASS 31
Mengkulang
Kapur
Keruing

EUROPEAN SPECIES

CLASS 32
Ash
Beech
Oak
Sycamore (Plane)

CLASS 33
Douglas-fir
Larch
Pine:
- Maritime
- Scots
- Jack

CLASS 34
Poplar:
- Grey
- Black Italian

Elm:
- Dutch
- Redwood

Larch:
- Hybrid

Pine:
- Lodgepole
- Corsican

Fir:
- Silver

CLASS 35
Elm:
- English

Spruce:
- Silka

Whitewood

CLASS 36
Pine:
- Radiata

Spruce
- Black
- Norway

Willow:
- White

Spruce:
- White
- Silka (UK, Eire)

CLASS 37
Poplar:
- Hybrid

North American Wood Species Ranked According to Relative Strength and Stiffness

Strongest	**21**
	01
(Dry)	**22**
	02
	11
	29
	04
	06
	03
	12
(Green)	**22**
	07
	13
Weakest	**14**

Appendix B: Climate Conditions 7/20/08 to 9/24/08 for Blacksburg, VA.

Date	Condition	Temp	RH	Wind Speed
7/20/08	Fair	93	45	4
7/21/08	Fair	92	41	11
7/22/08	Fair	90	66	5
7/23/08	Cloudy	82	60	1
7/24/08	Fair	79	40	8
7/25/08	Cloudy	81	43	7
7/26/08	Partly Cloudy	86	51	3
7/27/08	Fair	85	51	15
7/28/08	Fair	88	33	0
7/29/08	Sunny	88	49	3
7/30/08	Partly Cloudy	88	55	5
7/31/08	Rain	81	75	4
8/1/08	Partly Cloudy	86	51	6
8/2/08	T-Storms	83	64	7
8/3/08	Partly Cloudy	84	46	8
8/4/08	Sunny	86	50	6
8/5/08	Cloudy	85	51	6
8/6/08	Cloudy	85	51	10
8/7/08	Rain	80	60	7
8/8/08	Partly Cloudy	79	40	10
8/9/08	Fair	79	34	8
8/10/08	Sunny	81	39	10
8/11/08	Partly Cloudy	74	45	11
8/12/08	Fair	80	29	6
8/13/08	Partly Cloudy	76	64	8
8/14/08	Fog	81	88	0
8/15/08	Fog	79	75	1
8/16/08	Fog	80	63	0
8/17/08	Partly Cloudy	81	44	3
8/18/08	Fog	84	50	0
8/19/08	Sunny	84	29	10
8/20/08	Partly Cloudy	85	37	5
8/21/08	Cloudy	81	51	5
8/22/08	Partly Cloudy	82	33	11
8/23/08	Cloudy	80	47	7
8/24/08	Partly Cloudy	84	38	8
8/25/08	Cloudy	86	43	3
8/26/08	Rain	63	95	8
8/27/08	Rain	64	85	14
8/28/08	Cloudy	68	90	0
8/29/08	Cloudy	79	63	5
8/30/08	Sunny	85	50	3
8/31/08	Partly Cloudy	81	65	12
9/1/08	Fair	81	58	7
9/2/08	Fair	83	42	8
9/3/08	Fair	86	55	0
9/4/08	Sunny	86	31	6
9/5/08	Showers	81	51	10
9/6/08	Cloudy	82	53	14
9/7/08	Fair	83	45	5
9/8/08	Partly Cloudy	85	47	5
9/9/08	Cloudy	71	84	6
9/10/08	Fog	68	77	2
9/11/08	Cloudy	70	45	4
9/12/08	Cloudy	82	62	7
9/13/08	Fog	88	81	5
9/14/08	Partly Cloudy	88	44	3
9/15/08	Partly Cloudy	75	52	6
9/16/08	Cloudy	64	78	3
9/17/08	Fair	73	53	0
9/18/08	Sunny	78	37	6
9/19/08	Cloudy	67	65	7
9/20/08	Fair	74	41	0
9/21/08	Fair	76	47	5
9/22/08	Fair	77	32	9
9/23/08	Partly Cloudy	74	45	9
9/24/08	Fair	72	41	13

Appendix C: Drying Cost Estimation

A.	Direct investments (total costs)		
	Buildings, sheds, etc.	________	(1)
	Kiln, auxiliary equipment	________	(2)
	Stickers	________	(3)
	Pile roofs	________	(4)
	Pile bases, bolsters	________	(5)
	Total direct investment lines 1 thru 5	________	(6)
B.	Amortization period for direct investments (years)	________	
	Buildings, sheds, etc.	________	(7)
	Kiln, auxiliary equipment	________	(8)
	Stickers	________	(9)
	Pile roofs	________	(10)
	Pile bases, bolsters	________	(11)
C.	Quantity of wood dried annually (M bm)	________	(12)
D.	Annual interest rate (% as decimal)	________	(13)
E.	Dry yard investments (total costs)		
	Storage shed for stickers, dried lumber, etc. (do not duplicate #1)	________	(14)
	Permanent road construction, rail access, etc.	________	(15)
	Temporary road construction, includes drying alleys	________	(16)
	Fences	________	(17)
	Lighting systems	________	(18)
	Drainage systems	________	(19)
	Sprinkler systems	________	(20)
	Total (lines 14 thru 20)	________	(21)
F.	Amortization period for drying yard investments		
	Storage shed for stickers, dried lumber, etc. (do not duplicate #1)	________	(22)
	Permanent road construction, rail access, etc.	________	(23)
	Temporary road construction, includes drying alleys	________	(24)
	Fences	________	(25)
	Lighting systems	________	(26)
	Drainage systems	________	(27)
	Sprinkler systems	________	(28)
G.	Maintenance and repair of yard, % of line 21 ($/yr)	________	(29)
	Plus snow removal ($/yr)	________	(30)
	Plus yard cleaning ($/yr)	________	(31)

Plus annual lighting expense (bulbs and electricity) ________ (32)

H. Land Area (ft^2)

Air drying area (include space between piles) ________ (33)

Road area (refers to line 15, roads) ________ (34)

Area for buildings, kiln, boiler, etc. ________ (35)

Total (lines 33 thru 35 ________ (36)

I. Land Value ($\$/ft^2$) ________ (37)

J. Taxable Values ($)

Land (line 36 times line 37) ________ (38)

Buildings (line 1) ________ (39)

Kilns, equipment (line 2) ________ (40)

Fences, lighting, drainage, sprinklers (line 17 + 18 + 19 + 20) ________ (41)

Total (lines 38 thru 41) ________ (42)

K. Insurable Values ($)

Direct Investments (line 6) ________ (43)

Storage sheds (line 14) ________ (44)

Fences (line 17) ________ (45)

Wood (line 62 times line 64) ________ (46)

Total (lines 43 thru 46 ________ (47)

L. Tax rate to be applied to line 42 (% as decimal) ________ (48)

M. Insurance rate to be applied to line 47 (% as decimal) ________ (49)

N. Stacking time (M bm/hr) ________ (50)

O. Hourly stacking cost (include machinery, labor, and fringe benefits ________ (51)

P. Forklift time (M bm/hr) (52)

Q. Hourly forklift cost (include machine cost, labor, and fringe benefits) ($/hr) ________ (53)

R. Time spent each day observing and running kilns, boilers, etc. (hr) ________ (54)

S. Hourly wage rate and fringe benefits for kiln operator and auxiliary equipment including boiler ($/hr) ________ (55)

T. Maintenance of kilns and boiler, a percentage of line 2 (in dollars) ________ (56)

U. Annual office costs attributed to drying (in dollars) ________ (57)

V. Energy costs (boiler costs should be included in lines 2 and 56, not here) ________ (58)

Annual fuel consumption (gal or 1,000 ft^3) ________ (59)

Annual electrical usage attributed to drying (kWh) ________ (60)

Electrical cost ($/kWh) ________ (61)

W. Average price of lumber ($/M bm) ________ (62)

X. Average drying degrade, based on lumber value ($ as decimal) __________ (63)

Y. Average daily volume of lumber on yard and in kilns on any given day (M bm) __________ (64)

Z. Total capacity of kilns __________ (65)

AA. Average length of kiln run (including loading and unloading time) __________ (66)

Appendix D: PDS Pallet Component Grades - Lumber Characteristic Restrictions

PDS Pallet Component Grades

Lumber Characteristic Restrictions

Lumber Characteristic	Pallet Component Grade				
	Select	**Premium**	**Standard**	**Utility**	**Economy***
Sound Knots	¼ of Cross Section <u>Stringer Notch Area</u>: 1/8 of Above Notch Cross Section	1/3 of Cross Section <u>Stringer Notch Area</u>: ¼ of Above Notch Cross Section	½ of Cross Section <u>Stringer Notch Area</u>: 1/3 of Above Notch Cross Section	¾ of Cross Section <u>Stringer Notch Area</u>: ½ of Above Notch Cross Section	7/8 of Cross Section <u>Stringer Notch Area</u>: 5/8 of Above Notch Cross Section
Unsound Knots, Loose Knots, Holes	1/8 of Cross Section	¼ of Cross Section	1/3 of Cross Section	½ of Cross Section	½ of Cross Section
Cross Grain	1 in 10	1 in 8	1 in 6	1 in 4	Not Limited
Localized Grain Disorientation	¼ of Cross Section	1/3 of Cross Section	½ of Cross Section	2/3 of Cross Section	Not Limited
Splits, Checks, Shake	¼ of Part Length	1/3 of Part Length	½ of Part Length	¾ of Part Length	Must not completely separate Component
Wane	1/16 of Cross Section <u>Stringers</u> or <u>Blocks</u>: 1/16 Nail Face x ¼ Height <u>Boards</u>: 1/8 Width x 1/3 Thickness (Any Length)	1/8 of Cross Section <u>Stringers</u> or <u>Blocks</u>: 1/8 Nail Face x 1/3 Height <u>Boards</u>: 1/6 Width x 1/2 Thickness (Any Length)	3/16 of Cross Section <u>Stringers</u> or <u>Blocks</u>: 1/3 Nail Face x 1/3 Height <u>Boards</u>: ¼ Width x 2/3 Thickness (Any Length)	1/4 of Cross Section <u>Stringers</u> or <u>Blocks</u>: 1/2 Nail Face x 1/2 Height <u>Boards</u>: 1/3 Width x Full Thickness (Any Length)	5/16 of Cross Section <u>Stringers</u> or <u>Blocks</u>: 5/8 Nail Face x 2/3 Height <u>Boards</u>: 1/2 Width x Full Thickness (Any Length)
Unsound Wood	None	1/8 of Cross Section	¼ of Cross Section	1/3 of Cross Section	1/2 of Cross Section
Pith	None	Not Limited	Not Limited	Not Limited	Not Limited
Mismanufacture	None	1/16 of Cross Section	1/8 of Cross Section	3/16 of Cross Section	¼ of Cross Section

* Economy Component Grade permits lumber characteristics which prevent reliable estimates of strength, stiffness, or durability.
Design Values are only available for components of Utility Grade and above.

References:

ANSI. Approved American National Standard. Pallets, Slip Sheets, and Other Bases for Unit Loads. MH1-2005. MH1 Secretariat. Charlotte, NC. 2005. http://www.mhi.org/downloads/free/mh1-2005_v07asf.pdf

B. Bond. Case Studies of Heat Treating and Mold Control of Wood Pallets. Brooks Forest Products Center. Blacksburg, Va. 2004.

Bausch & Lomb. Fox news. Contact Lens Fungus Linked to ReNu. Wednesday April 12, 2006. http://www.foxnews.com/story/0,2933,191378,00.html. 12/12/07.

Blank, L. & Tarquin, A. (2005). Customized Version of Engineering Economy. Boston: McGraw Hill.

Bowyer, Shmulsky, Haygreen. Forest Products and Wood Science. An Introduction. 4th ed. 2003. pgs. 265-268.

Browner, Carol; Glickman, Dan. 1999. Waste Not, Want Not: Feeding the Hungry and Reducing Solid Waste Through Food Recovery. December 22, 1999. http://www.epa.gov/epaoswer/non-hw/reduce/wastenot.htm.

Cassens, Daniel L. Department of Forestry and Natural Resources. Cooperative Extension Service Purdue University. Sap Stain in Hardwood Logs and Lumber. 1991. FNR-90.

Clarke, John. Pallets 101: Industry Overview and Wood, Plastic, Paper & Metal Options. Grate Pallet, Inc., Posted 7/1/2005

Clausen, Carol A.; West, Michael. 2005. Test Method for assessing resistance of pine lumber and waferboard to mold. *Forest Products Journal* 55(12): 164-166. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Denig, Joseph. December 1980. Thesis: An Air Drying Index Using Meteorological Data For Appalachian Hardwood Lumber. Blacksburg, VA.

Denig, Joseph. NCSU. April 2002. Wood Products Notes. Heat Sterilization of Hardwood Pallets and Pallet Material. http://www.ces.ncsu.edu/nreos/wood/wpn/pallets.html

DOE. September 2008. Energy Information Administration. Official Energy Statistics from the U.S. Government. Department of energy. Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State, September 2008 and 2007. Report No.: DOE/EIA-0226 (2008/12). http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_a.html

Gaston, Christopher W., Mckeever, David B., Tabarsi, Erfan. Wood Products Council. Wood Used in Industrial Markets. Sept. 2002. p26.

Hamner, Peter. Center for Unit Load Design. WERC Project Application – Part II. Evaluation of Methods to Control Mold on Hardwood Pallets: A Manufacturers Perspective. 2007.

Hoadley, R. Bruce. Understanding Wood: A Craftsman Guide To Wood Technology. Wood and Water. 2000. p115.

ISPM. 2008. International Standards of Phytosanitary Measures No. 1 to 31. ISPM #15: Guidelines for Regulating Wood Packing Material in International Trade. Approved Measures Associated with Wood Packaging Material. p. 203.

Johnson, Lance. ISK Biocides Inc., Memphis, Tn. Presentation: *Lumber Stains: Cause and Control*. 2007.

Lamb, Fred M., 2002. The Importance of Air Velocity in Drying: How air speed through the kiln affects lumber seasoning.

Lamb, Fred M. Operating an Effective Air Drying Yard. Department of Wood Science and Forest Products, Brooks Forest Products Center. Virginia Tech. Blacksburg, VA.

McMillen, John M., and Wengert, Eugene M. 1978. Drying Eastern Hardwood Lumber. Agriculture Handbook No. 528. Forest Products Laboratory. Forest Service. U.S. Department of Agriculture.

Nyle Dry Kiln Systems. Introduction to Kiln Drying: *Straight Forward Answers to 24 Important Questions.* Bangor, ME. http://www.nyle.com/downloads/KilnDrying.pdf. Accessed 3/9/2009.

NWPCA. 2006. PDS Pallet Component Grades – Lumber Characteristic Restrictions. www.nwpca.com/PDS/Table-ComponentGrade-LumberCharacteristicRestrictions.pdf

Rasmussen, E.F. 1961. Dry Kiln Operator’s Manual. USDA Agr. Handbook No. 188. 197 pp.

Reeb, J. & Brown, T. 1995. Air- and Shed-drying Lumber. Oregon State University Extension Service

Robbins, Coreen and Morrell, Jeff. 2006. Mold, Housing and Wood. Western Wood Products Association. 11 p.

Sampson, George R.; Ruppert, Forrest A. 1985. Air drying of softwood lumber, Fairbanks, Alaska. Res. Pap. PNW-340. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 6 p.

Simpson, William T. 1997. Effect of air velocity on drying rate of single eastern white pine boards. Res. Note FPL-RN-266. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products laboratory. 5p.

Simpson, William T. 2004. Estimating air drying times of lumber with multiple regression. Res. Note FPL-RN-0293. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 6 p.

Simpson, William T.; Hart, Arthur C. 2000. Method for Estimating Air-drying times of Lumber. Forest Products Laboratory. *Forest Products Journal* 51(11/12):56-63

Simpson, William T and Boone, Sidney R. 2001. Kiln Operator's Manual. USDA Agr. Handbook No. 188.

Simpson, William T and Wang, Xiping. 2003. Estimating air-drying times of small-diameter ponderosa pine and Douglas-fir logs. Forest Products Laboratory. *Forest Products Journal* 54(12). 5.

Simpson, William T.; Wang, Xiping; Forsman, John W.; Erickson, John R. 2005. Heat Sterilization Times of Five Hardwood Species. Res. Pap. FPL-RP-626. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 10 p.

Taylor, Adam M.; Freitag, Camille M.; Morrell, Jeffrey J. 2002. Ability of bleach and other biocide treatments to remove and prevent mold growth on Douglas-fir lumber. Oregon State University. *Forest Products Journal* 54(4):45-49.

Tschernitz, John L. Chapter 11: Energy in Kiln Drying. Dry Kiln Operator's Manual. 1991.

Twede, Diana and Selke, Susan E. M.. 2005. Cartons, Crates, and Corrugated Board. Handbook of Paper and Wood Packaging Technology. pg 155-163.

United States Department of Agriculiture. USDA. Forest Products. July 1999. Techline. Decay Process and Bioprocessing. Mold and Mildew on Wood: Causes and Treatment. www.fpl.fs.fed.us/

Volk, Thomas J. Tom Volk's Fungus of the Month for November 2004. Department of Biology. University of Wisconsin-La Crosse.

WebMD. http://www.webmd.com/allergies/guide/mold-allergy. Allergies: Mold Allergy. September 25, 2007.

Wengert, Eugene M. The Wood Doctor's. 1996. Wood Supplies: Today and Tomorrow. Ch. 1.

Western Wood Products Association. WWPA. Fast Facts. Mold and Wood Products. No. 2: Preventing and Controlling Mold. www.wwpa.org.

Western Wood Products Association. WWPA2. http://www2.wwpa.org/SERVICES/ProductSupport/MoldHousingandWood/tabid/420/Default.aspx#what.

White, Marshall. 1998. Water in Wood Pallets: The Facts Behind the Opportunity Available to Dry Pallets. Sardo Pallet & Container Research Laboratory, Virginia Polytechnic Institute and State University.

White, Marshall. Overview of the US Pallet Industry. Nov. 2004. http://www.unitload.vt.edu/presentations/Korea.pdf.

White, Marshall; Hamner, Peter. 9/2/2003. Mold, Mildew on Pallets, Lumber can be Prevented, Eliminated. http://www.palletenterprise.com/articledatabase/view.asp?articleID=967.

White, M.S. and F.M. Lamb. 2002. Performance Evaluation of the Pest-Heat™ Thermal Pest-Heat™ Management System for the Heat Sterilization of Wood Pallets. William H. Sardo Jr. Pallet and Container Research Laboratory. Blacksburg, VA.

Williams, Robert C. Ph.D. Impact of Mold in the Food Processing Environment. Virginia Tech. Department of Food Science and Technology.