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Development of an in-kiln monitoring system based on acoustic emission rates of wood during the low-temperature drying process

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Development of an in-kiln monitoring system based on acoustic emission rates of wood during the low-temperature drying process

Shelstrom, Marc Reynold, Ph.D.

Iowa State University, 1994

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Development of an in-kiln monitoring system based on acoustic emission rates of wood during the low-temperature drying process

by

Marc Reynold Shelstrom

A Dissertation Submitted to the Graduate Faculty in Partial Fulfillment of the Requirements for the Degree of DOCTOR OF PHILOSOPHY

Department: Industrial Education and Technology
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For the Graduate College

Iowa State University
Ames, Iowa

1994

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CHAPTER I: INTRODUCTION

Despite technological advances in equipment, the basic process of kiln drying hardwood lumber has changed very little since the publication of Harry Tiemann's manual *The Kiln Drying of Lumber* in 1917. The basic process can be described as the placing of hardwood in an environment that consists of defined space, controlled temperature, controlled humidity, and controlled air flow. Hardwood kiln schedules\(^1\) have been developed over the years based on empirical knowledge and are used today to determine the rate at which wood is dried.

Kiln schedules have been developed to create a balance between the length of drying time and the amount of acceptable drying degrade. A compromise is reached between the length of drying time for the kiln charge and the amount of acceptable drying degrade. This compromise translates directly into operating costs. Longer, slower drying times increase overhead costs while shorter, faster drying times produce low quality or unusable wood.

A kiln schedule is designed to control the rate of drying for a particular species and thickness of wood by using a series of steps that increase drying temperature and decrease drying humidity. A step change is determined when a desired moisture content has been reached in the

\(^1\)From now on, the term hardwood kiln schedule will be shortened to kiln schedule.
In the basic drying process, the kiln charge is very carefully constructed to minimize degrade. The charge is placed in the kiln and dried according to the kiln schedule. After the drying process has been completed, the wood is removed from the kiln and examined for drying defects. This method requires examining each piece of wood if the defects are to be found.

The drying process just described is based on the manufacturing model of input, process, output, and feedback, which is used by the traditional wood drying industry (Figure 1).

![Image of the drying process model]

Figure 1. Present wood drying manufacturing model
American manufacturers have started to examine and, in many cases, have adopted a much different manufacturing model. This new model is based on product quality improvement using the teachings of Deming, Juran, and others.

The philosophies and methods of Continuous Product Improvement\(^2\) (CPI) are being introduced in all types of industries and educational institutions. The impact of CPI has been demonstrated very clearly by the success of the Japanese manufacturing industry.

One of the recognized CPI philosophies is Dr. Edward Deming's Total Quality Management (TQM) philosophy which consists of fourteen points designed to improve a company and ultimately its product quality.

One of the points of Deming's TQM is to cease dependence on mass inspection. Mary Walton interviewed Deming concerning this point, and he responded as follows:

Inspection with the aim of finding the bad ones and throwing them out is too late, ineffective, and costly. In the first place, you can't find the bad ones, not all of them. Second, it costs too much. Quality comes not from inspection but from improvement of the process (Walton, 1986, p. 60).

\(^2\)Continuous Product Improvement is the term used in this study to represent the vast number of names given to the subject of quality improvement.
Statistical process control (SPC) is one method used by industry to lower or cease dependence on mass inspection. The first step in using SPC requires a monitoring system that gathers enough relevant data at the right time during the processing step. The relevant data is then used to determine if the process needs to be adjusted to improve product quality (reduce variability). A model for the hardwood drying industry based on Continuous Product Improvement is illustrated in Figure 2.

Figure 2. Basic quality improvement model
An examination of Figure 2 shows two opportunities exist where customer satisfaction may be improved. Loop A focuses on meeting the customers' changing needs and expectations. Loop B represents a monitoring system taking direct measurements of the output during the processing step. Using these measurements from Loop B, statistical process control can be used to determine when adjustments need to be made to improve quality (Garrity, 1993; Kane, 1989). In the case of wood drying, using the Basic Quality Improvement Model would in theory reduce the amount of drying degrade and therefore increase profit.

Statement of the Problem

The problem confronting the wood drying industry is that no method exists that allows for continuous monitoring of the wood during the traditional drying process. Indirectly the process is monitored by the drying schedules that have been developed empirically over the years. These drying schedules accept a compromise between drying degrade and total drying time for a kiln charge. An in-kiln monitoring system would be the first step in acquiring data that could be the basis for the application of SPC to improve the wood drying process.

A method that holds promise as the basis for an in-kiln monitoring system is the measurement of acoustic emissions (AE). As wood is dried, it shrinks, and as it shrinks, stresses are induced into the wood. When the
induced stress becomes of sufficient magnitude, it causes microscopic tissue ruptures to form. As each microscopic rupture forms, small bursts of sound energy or acoustic emissions are released. As the rate of AE increases, the microscopic ruptures develop into visible tissue ruptures. Thus AE rate gives an early indication of future drying degrade (Quarles, 1992; Honeycutt, Skaar & Simpson, 1985; Becker, 1982; Noguchi, Kagawa & Katagiri, 1980).

Purpose of the Study

The central purpose of this study was to determine if an in-kiln monitoring system based on the acoustic emission rates of wood as it dries could be developed to monitor the traditional kiln drying process.

Research Questions

The following questions were addressed by this study.

1. What does a typical acoustic emission event look like when a polyvinylidene fluoride sensor is used as an acoustic emission sensor?

2. What are the characteristic acoustic emission rates for the first seven kiln steps within the drying schedule?

---

3Visible tissue rupture can be categorized into the following types: surface checks, end checks, end splits, honeycomb, and collapse.
3. What are the stress/strain characteristics for the first seven steps within the drying schedule?

4. What are the characteristic tissue rupture rates for the first seven kiln steps within the drying schedule?

5. What are the characteristic collapse rates for the first seven steps within the drying schedule?

6. Does a relationship exist between acoustic emission rate and tissue rupture?

7. Does a relationship exist between acoustic emission rate and casehardening?

8. Does a relationship exist between acoustic emission rate and collapse?

Research Hypotheses

Based on the aforementioned research questions, the following null hypotheses were tested.

1. There are no significant differences between the acoustic emission rates for the first seven kiln steps within the kiln schedule.

2. No relationship exists between casehardening and acoustic emission rates.
3. No relationship exists between the amount of tissue rupture and acoustic emission rates.
4. No relationship exists between collapse and acoustic emission rates.

Delimitations of the Study
1. This study examined bur oak heartwood (*Quercus macrocarpa* Michx.) in the following conditions.
   A. Rough-sawn (surface quality)
   B. Quarter-sawn (annual ring orientation)
   C. Mature wood
2. This study was based on the drying schedule for white oak as defined in the *Dry Kiln Operator's Manual* (1987).
3. This study examined only three areas of drying degrade: tissue rupture, casehardening, and collapse.

Assumptions of the Study
1. The bur oak samples used in this study had acoustic emission rates typical of the species as a whole.
2. The use of polyvinylidene fluoride film was a valid and reliable method to measure the acoustic emission rates of wood being dried.
3. All data recording equipment gave valid and reliable readings.

4. Electromagnetic interference was not at a significant level to interfere with data collection.

Definition of Terms

The following terms were used for the purpose of this research.

**Casehardening** - dried lumber with nearly uniform moisture content but characterized by the presence of residual stresses. During early stages of drying, the wood shell is in tension and the core is in compression. In the last stages of drying, the shell is in compression and the core is in tension.

**Checks** - tissue rupture that develops along the grain and usually extends across the annual ring parallel to the rays. Checks can be of two types: surface and end.

**Collapse** - a defect that develops above the fiber saturation point when very wet heartwood of certain species is dried. Collapse is characterized by buckling or abnormal shrinkage in the wood.

**Conditioning** - a process to relieve casehardening stress. The temperature is set to the last kiln step's criteria, and the conditioning EMC is set to 4% above the desired final moisture content.

**Creep** - increase in strain over time

**Drying degrade** (drying defect) - any irregularity induced into the wood during the drying process which lowers the strength, durability, usability, or
value of the wood

**Elastic region** - the area represented on a stress/strain curve in which a material under stress is deformed below the proportional limit, but when the stress is removed, the material returns to its original size

**End splits** - end checks that have developed into very large splits

**Equalization** - a process to bring the pieces within the kiln charge to approximately the same moisture content. When the driest kiln sample reaches 2% below the desired final moisture content, the temperature and relative humidity are set to establish drying conditions that will achieve the desired final moisture content.

**Equilibrium moisture content (EMC)** - the moisture content wood will come to when placed in a given temperature and relative humidity environment

**Fiber saturation point (FSP)** - the point in which the cell wall is fully saturated with water and the cell lumen is empty of free water

**Flat-sawn** - lumber sawn so that the annual ring orientation makes an angle of less than 45° to the wide surface of the board

**Heartwood** - the wood that extends from the pith to the sapwood or the central part of the tree trunk. The heartwood is not involved with the life processes of the tree.

**Honeycomb** - tissue rupture that develops in the interior of wood as a result of drying stress
Juvenile wood - wood formed early in a tree's life and found near the center of the trunk

Kiln charge - the total amount of lumber that can be loaded into the kiln for each drying cycle

Plastic range - the area represented on a stress/strain curve in which a material under stress is deformed above the proportional limit but when the stress is removed, the material does not return to its original size

Proportional limit - the point between the elastic range and the plastic range

Quarter-sawn - lumber sawn so that the annual ring orientation makes an angle of greater than 45° to the wide surface of the board

Rough lumber (RLG) - the surface quality of the lumber as it comes from the primary breakdown saw

Sapwood - the wood that extends from the heartwood to the bark. Generally lighter in color than heartwood, the sapwood is involved with the life processes of the tree.

Set - material deformation that remains after the release of stress

Strain - deformation as the result of induced stress

Stress - force per unit area

Tension wood - forms on the top side of leaning hardwood trees or branches and has very different shrink/swell properties than wood in non-leaning hardwood trees
Tissue rupture - separation of wood fiber caused by drying stress and includes the following: honeycomb, splits, checks, and collapse

Traditional or industrial drying process - the basic kiln drying process that uses defined space, controlled temperature, controlled humidity, and controlled air flow

Procedure of the Study

The following steps outline the procedure used in conducting the study.

1. The researcher conducted a review of literature.
2. Experts in the field of wood drying and acoustic emission were consulted to ascertain the need for an in-kiln monitoring system.
3. Electronic instruments were designed and built to visually view acoustic emissions as displayed on a digital storage oscilloscope.
4. The acoustic emission monitoring instruments were refined to eliminate electromagnetic interference.
5. Electronic equipment was designed and built that would be able to monitor six wood samples in the kiln. The system was controlled by a computer that automatically chose wood sample/sensors to monitor and record AE data.
6. A computer program in "C" language was written to control the computer and all data acquisition.
7. The monitoring system was pilot tested in actual drying conditions.

8. The monitoring system was adjusted based on the pilot test.

9. The drying experiment was run, and acoustic emission data was collected by the monitoring system.

10. The data was analyzed using Excel, Quattro Pro, and SPSS software packages.

11. The final report was written basing conclusions and recommendations on the study findings.

12. The complete study report was presented to the program of study committee for final approval.
CHAPTER II: REVIEW OF LITERATURE

Wood that is sawn from logs has very unstable properties if left to dry on its own. Wood can rot, warp, and split if not dried properly. The wood drying process may be the most critical step in the wood manufacturing industry. The drying of wood has three positive effects. It controls biological degrade; it drastically reduces subsequent change in dimension; and it increases strength. However, the wood drying process can also have one negative effect. It can cause degrade in the form of tissue rupture and warp (Nicholas, 1973).

Basic Drying Process

Moisture in wood exists in two basic forms: bound water and free water. Water that is physically bound within the cell wall is known as bound water. Water in the cell lumen, which is the hollow center of the cell, is called free water. As green wood dries, the first water to leave the cell is free water because the forces holding it are weaker than the forces holding the bound water. The loss of free water from the cell lumen doesn't cause any dimensional change. The removal of bound water from the cell wall is accompanied by a reduction in thickness of the cell wall. The point at which a cell lumen contains no free water but may contain water vapor while the cell wall is saturated is known as the fiber saturation point (FSP). The FSP generally ranges from 20% to 40% moisture content (MC) depending on the
species (Skaar, 1988).

The mechanical properties of wood increase in strength as the wood dries below the fiber saturation point (FSP). For example, the modulus of rupture and the compression parallel to the grain both increase 4% for each 1% decrease in moisture content below the FSP (Boding and Jayne, 1982).

As wood dries below the FSP, it shrinks. Wood is an anisotropic material; it does not shrink and swell the same amount in each of its three principal directions. In the longitudinal direction, wood shrinks 0.1% to 0.3% while shrinkage in the tangential direction is generally twice that of the radial direction (Siau, 1984). The amount of anisotropic shrinkage that occurs during the drying process is species dependent. When white oak is dried from the green condition (above FSP) to the oven dry condition (zero percent moisture content), it shrinks 8.8% tangentially and 4.4% radially (Forest Products Laboratory, 1987). The forest products industry ignores the insignificant longitudinal shrinkage.

Differential shrinkage due to the anisotropic nature of wood causes wood to change its shape while the differential shrinkage due to reaction and juvenile wood properties are the main causes of warp (Simpson, 1991).^4

^4The problems associated with warp were not the focus of this study and will not be further addressed. The focus of this study was the problems associated with differential shrinkage between the shell and core as the drying process progresses from the green condition to below the fiber saturation point.
Wood dries from the outside to the inside, which creates a moisture gradient within the wood. The surface of the wood has dried, but the center has not. Differential shrinkage between the surface and the core is responsible for tissue rupture and casehardening (Panshin & de Zeeuw, 1980).

Collapse is another drying defect that can develop in certain wood species with very wet heartwood. Collapse begins before normal shrinkage begins. Normal shrinkage is the result of the cell wall material drawing together from the loss of water molecules from within the cell wall. Collapse is the result of the cell walls being pulled together, i.e., buckling into the cell lumen by the rapid loss of free water (Panshin & de Zeeuw, 1980).

Wood is a hygroscopic material. It loses and gains moisture based on the environment. Wood will come to an equilibrium moisture content (EMC) based on the relative humidity and temperature of the environment. Figure 3 depicts the effect of relative humidity and temperature on EMC (Dry Kiln Operator's Manual, p. 8). In examining Figure 3, if the temperature of the environment is 70°F and relative humidity is 75%, the wood will eventually come to an EMC of 15%.

The kiln schedule for white oak contains nine steps. Each of these steps utilizes two temperatures. The dry-bulb temperature is the actual drying temperature. The difference between the dry-bulb temperature and the wet-bulb temperature is used to control the level of relative humidity.
Figure 3. Relationship of EMC to temperature and humidity

in each kiln schedule step. For example, in step one, the dry-bulb temperature is 110° F and the wet-bulb temperature is 106° F, creating an in-kiln drying environment of 110° F and a relative humidity of 87%. If wood is left in these conditions long enough, it will come to an EMC of 17%. Each step in the kiln schedule is designed to take the wood to a lower MC by increasing temperature and lowering relative humidity levels.

Moisture movement during the drying process takes place in two phases: moisture movement from the interior of the wood to the surface and
moisture movement from the surface to the surrounding air (Simpson, 1991).

As wood dries, water moves within the wood from areas of high moisture content to areas of lower moisture content. As a result, a moisture gradient forms between the drier surface and the wetter interior zones (McMillen, 1955; Panshin & de Zeeuw, 1980).

Figure 4 (Dry Kiln Operator's Manual, p. 9) depicts a set of successive curves that represent the movement of the moisture gradient from the surface to the core as the wood dries. T₁, T₂, and T₃ represent increasing drying time.

The result of a developing moisture gradient moving through the wood causes stresses and strains to occur due to restrained shrinkage (Kass, 1965). Four key factors that underlie stress development in the drying process are as follows:

1. Wood will shrink or attempt to shrink when any portion dries below the fiber saturation point.
2. When wood is restrained from shrinking, it will develop tensile stresses.
3. If tensile stress is present in one part of a member due to internal restraint from shrinkage, it must be offset by compression stress in the portion doing the restraining.
4. Stresses in wood will cause deformation or strain in the member. If the stress is not too great or does not occur gradually over a long period, the deformation is elastic; i.e., the wood will recover its original size and shape when the stress is removed. If the stress increases beyond a certain point (the proportional limit) or if it has been applied slowly for a long period of time, the wood will not fully recover when the stress is removed. The
unrecovered deformation is called set. If the stress exceeds the strength of the wood, failure will occur (Stumbo, 1986, pp. 69-70).

Stress is usually thought of as external forces acting on an object, but stresses still develop in the wood drying process although no external forces are involved. Moisture removal below the FSP creates internal forces within the wood fibers. The internal forces cause submicroscopic deformations (strain) within the cell wall. These forces cause the cell wall to shrink. If the wood is restrained from shrinking, the internal forces will cause tensile stress in the wood (Stumbo, 1986).

In a study of restrained drying stresses, Kass (1965) measured tensile forces perpendicular to the grain and found them to be as high as 355 psi for aspen and 461 psi for oak. The drying conditions used in Kass's study were at a temperature of 85° F and an EMC of 4%.

Figure 5 (McMillen, 1955, p. 38) displays a typical stress/strain graph for wood and is used graphically to help explain the stresses and strains induced by the movement of a moisture gradient. As a moisture gradient develops, the surface layer dries faster than the slower drying core. Once the surface moisture goes below the FSP, the surface layer will try to shrink. However, the surface is restrained by the core that is still above the FSP. The restrained shrinkage of the outer layer causes tensile stresses to develop in the outer layers and compressive stresses to develop in the core.
As tensile stresses begin to develop, the submicroscopic deformations (strain) in the fibers are in the elastic range and therefore are recoverable. If tensile stresses continue to build as the moisture gradient moves through the wood, the tensile stresses will exceed the proportional limit and the

Figure 5. Typical stress-strain graph for wood
deformation (strain) is now in the plastic range. In the expanded state of plastic deformation the internal structure of individual fibers realign. When the tensile stress is removed, the wood will recover the elastic portion of deformation, but it will not recover any plastic deformation. The nonrecoverable plastic deformation is called set. If tensile stresses continue to increase, they will reach the ultimate stress of the wood and tissue rupture occurs.

As the wood continues to dry and the moisture gradient moves towards the core, the zone attempting to shrink also moves toward the core. The outer layer becomes drier and drier. As it becomes drier, it is set to a dimension close to the original green dimension. When the set in the outer shell progresses to where the interior zone starts to go below the FSP, the stresses reverse. Then the core is under tensile stress and the exterior is under compressive stress.

During the first stage, when the shell is in tension and the core is in compression, surface and end checks tend to form. During the second stage, when the shell is in compression and the core is in tension, honeycomb tends to form (Erickson & Seavey, 1992; Stumbo, 1986).

Slice Test

The slice test is a method used to measure the amount of strain that is induced into the wood by drying stress. Figure 6 is a graphic
Figure 6. Slice test moisture stress relationship
Figure 6. (continued)
representation of the strain that results from the moisture gradient movement. The seven sets of three figures each represent the kiln steps in a drying schedule. Each step's three squares are divided into ten equal slices, and each square's slice displays either unrestrained shrinkage, restrained shrinkage, or associated moisture gradient. Step 1A - C represents the wood at the beginning of the drying process. Steps 2A - C through 4A - C represent the buildup of tensile stress in the shell to a maximum and a simultaneous buildup of compressive stress in the core to a maximum. Starting with Step 5A - C, the stresses reverse with the compressive stress switched to the shell and tensile stress switched to the core. The compressive stress in the shell and the tensile stress in the core build simultaneously to a maximum in Step 7A - C.

The slice test enables the researcher to measure the strain induced in
the wood at the end of each kiln step by slicing samples into pieces of equal width. The slices are measured before and after slicing, and a strain value is computed. The actual stress induced into the wood during drying is not calculated, but the determined strain gives a representation of the changing tensile and compressive stress. The moisture content of each slice is also determined to establish the moisture gradient (Erickson & Seavey, 1992; McMillen, 1955; Simpson, 1991).

Prong Test

The prong test is a visual test that determines the extent or severity of casehardening. Figure 7 (Dry Kiln Operator’s Manual, p.126) shows four prong test samples that were cut to determine if casehardening is present after equalization. Test sample A shows no casehardening while sample C shows a severe case of casehardening. Casehardening can be relieved by creating an environment of high humidity in the kiln. The shell of the wood takes on moisture, thus relieving stress buildup. The wood must be monitored constantly by cutting new prong test samples to make sure the wood does not experience reverse casehardening as shown in Figure 7D. Reverse casehardening can not be removed, rendering the wood useless for high quality industrial purposes. If casehardening stresses are not removed, when the wood is machined, it will distort as shown in Figure 7C. Again the wood is rendered useless as a high quality industrial material.
Acoustic Emission Application to the Wood Drying Process

Acoustic emissions (AE) are ultrasonic signals produced when there is a sudden inelastic, localized change in stress accompanied by an inelastic deformation (Miller & McIntire, 1987).

Acoustic emissions produced during the drying process are the result of small internal microscopic ruptures. These microscopic tissue ruptures are the result of tensile drying stresses. The acoustic emissions can serve as a precursor to larger visible tissue ruptures such as checking and honeycombing (Honeycutt, Skaar, & Simpson, 1985; Skaar, Simpson, & Honeycutt, 1980).
Noguchi, Kagawa, and Katagiri (1980) studied the drying of oak and beech and found AE rates did not increase with an increase in temperature, but AE rates increased with a decrease in humidity and decreased with an increase in humidity. The AE rates responded with more sensitivity to changes in relative humidity than to changes in the internal moisture content of the wood when the MC was reduced at a constant low rate. It was also found that AE rates were species dependent as oak produced much higher AE rates than beech.

Becker (1982) found a positive relationship between drying severity and the rates of AE produced during the drying of small pine samples in a laboratory kiln. The results of the study show that the AE rate increased rapidly toward a maximum rate and then tapered off more slowly toward zero as the wood approached EMC.

During the drying of oak, beech, and birch, Nogucki, Kagawa, and Katagiri (1983) found much the same results as they did in their 1980 study. Temperature had little effect on the AE rate. Relative humidity was related inversely to the AE rate. AE rates once again were species dependent with oak producing the highest AE rates.

Honeycutt, et al. (1985) dried red oak from green to 20 percent moisture content at a constant wet-bulb temperature of 35°C and a varying dry-bulb temperature between 35°C to 59°C. The study examined the feasibility of using AE rates as a control of the drying process. The AE rate
was held to 1000 events per minute by adjusting the dry-bulb temperature. The results of the study supported the hypothesis that wood could be dried on the basis of AE rate alone. Another important finding of the study was that AE rate was an early indicator of an out-of-control drying process.

Noguchi, Kitayama, Satoyoshi, and Umetsu (1987) used AE parameters to control the drying conditions and confirmed experimentally that AEs could be an early warning that drying defects would develop. *Zelkova serrata* disks were dried through in-process AE monitoring. It was found that the AE event count rate and the average increasing rate had considerable effect on the prediction of checking, but cumulative AE rates had little effect.

Quarles (1992) found that the high peak amplitude AEs were associated consistently with the propagation of surface checks. He also found that low amplitude AEs were associated with precursor activity that led to the development of microchecks that in turn led to visible checks. Quarles studied California black oak 25 mm and 50 mm thick under constant drying conditions of 82° C dry-bulb temperature and 43° C wet-bulb temperature.

Acoustic emission's greatest potential lies in its ability to provide information to monitor a structure or a process continuously, on-line, and in real time. A process or material that is producing AEs is in effect talking about itself. The problem becomes one of developing a system that
processes AE signals into usable information (Sachse & Grabec, 1992). A monitoring system based on AE information must perform three functions: (1) detect the signal, (2) process the signal, and (3) evaluate the data in order to make any necessary adjustments to the process (Sachse, 1991).

**Statistical Process Control Charts**

Statistical process control (SPC) is based on identifying two types of variations. Common cause variation, which is inherent to the process and occurs naturally, can be eliminated only by improving the process technology. Examples of common cause variability are machinery, materials, and measurements. Special cause variations are factors that can be identified and eliminated such as worn tools or human error (Garrity, 1993; Gelina, 1988).

Statistical process control is a method that uses charts based on statistical data that can be used to monitor quality conformance and to indicate when a process is out of control (Evans & Lindsey, 1989). Statistical process control charts provide the opportunity to determine if a sequence of data may be used for predicting what will occur in the future. The use of SPC charts provides a technique for inductive inference. Inductive procedures involve the extrapolation from specific events back to general principles. The movement from specifics to generalities is never clear cut and will involve some degree of uncertainty. Control charts
provide the means to use an inductive technique that addresses real-world problems through prediction. Control charts predict when a process is stable. They can also predict instability or uncontrolled variation. Control charts are powerful tools for detecting uncontrolled variations and are effective with virtually any type of data (Shewhart, 1931; Shewhart & Deming, 1939; Wheeler & Chambers, 1992).

Summary of the Review of Literature

Wood in the green state is very unstable in terms of decay resistance, dimensions, and strength. Removal of free water from the cell lumen increases wood's ability to resist decay. Removal of water from the cell wall tremendously increases wood's strength but also causes wood to degrade by either warp or tissue rupture. Tissue rupture is caused by the tensile stress induced into the wood as the result of a moisture gradient moving through the wood as it dries. One other problem associated with certain species of wood when dried is collapse. Collapse is caused by removing free water from the cell lumen at too rapid a rate, causing the cell wall to collapse into the lumen.

If the stress created by the drying process is great enough, beyond the ultimate strength of the wood, small microscopic tissue fractures are formed. These small fractures give off bursts of sound energy, acoustic emissions (AE), that are measurable. The small microscopic fractures are
precursors to all forms of tissue rupture.

Acoustic emissions offer a means to monitor the drying process continuously, on-line, and in real time. Many researchers found that humidity has the greatest effect on acoustic emission rates while temperature has very little effect (See Table 1). Previous studies found that as relative humidity decreases, AE rates increase, and as relative humidity increases, AE rates decrease.

Table 1. Researchers who found that relative humidity affects AE rate

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Year</th>
<th>Wood Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Becker</td>
<td>1982</td>
<td>Pine</td>
</tr>
<tr>
<td>Noquoki, Kagawa, &amp; Katagiri</td>
<td>1983</td>
<td>Oak, Beech, and Birch</td>
</tr>
<tr>
<td>Honeycutt, Skaar, &amp; Simpson</td>
<td>1985</td>
<td>Red Oak</td>
</tr>
<tr>
<td>Noquoki, Kitayama, Satoyshi, &amp; Umetsu</td>
<td>1987</td>
<td><em>Zelkova serrata</em></td>
</tr>
<tr>
<td>Quarles</td>
<td>1992</td>
<td>Black Oak</td>
</tr>
</tbody>
</table>

A phenomenon is said to be controlled when through the use of past experience it can be predicted, at least within limits, how the phenomenon may vary in the future (Shewhart, 1931, p.6). Shewhart, who is considered by many to be the father of statistical process control (SPC), stated that statistical process control charts are powerful tools that can detect
uncontrolled variations in virtually any type of data. SPC provides the opportunity to use and understand what acoustic emissions are tell about the drying process.
CHAPTER III: METHODOLOGY

This study sought to ascertain if a dry kiln monitoring system could be developed based on the acoustic emission rates of wood as it progresses through the drying process.

Upon completing the problem identification, writing the literature review, and receiving approval of the research proposal, the following methods and procedures were used to investigate the problem:

1. Species harvesting and sampling
2. Kiln schedule development
3. Drying process and data acquisition
4. Data analysis
5. Presentation of the summary, conclusions, and recommendations of the study

In this chapter descriptions of the species harvesting and sampling, the kiln schedule development, the drying process, and the data acquisition are presented.

Species Harvesting and Sampling

The white oak sub genus, specifically bur oak (*Quercus macrocarpa* Michx.), was chosen for this study due to its availability to the researcher and its tendency to tissue rupture during the drying process. Two trees were cut down on a farm located in Winneshiek County in northeastern
Iowa. The characteristics of the trees are shown in Table 2.

Both trees were selected for straightness to help eliminate adverse drying effects caused by tension wood.

Each tree stem was taken to a sawmill and sawn into 1 1/8 inch thick boards. The ends of each board were endcoated to prevent excessive moisture loss. Each of the stem's boards was labeled with either a T1x or T2x number.

Table 2. Trees chosen for the study

<table>
<thead>
<tr>
<th>Tree Criteria</th>
<th>Tree 1</th>
<th>Tree 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem length to the first major branch</td>
<td>14'-2&quot;</td>
<td>18'-4&quot;</td>
</tr>
<tr>
<td>Stem diameter at breast height (4.5' above ground)</td>
<td>18.5&quot;</td>
<td>18.75&quot;</td>
</tr>
<tr>
<td>Number of annual rings at stump height</td>
<td>122</td>
<td>127</td>
</tr>
</tbody>
</table>

Each stem's boards were separated on the basis of annual ring orientation -- less than 45° to the wide surface (flat-sawn) and greater than 45° to the wide surface (quarter-sawn). Only quarter-sawn lumber was used for samples.

A random sample of three quarter-sawn pieces was chosen from each stem (T1 and T2). These samples were combined to become the study sample and were renumbered. The six pieces chosen as the kiln sample had
all their sapwood removed. Also, to eliminate juvenile wood, no wood was included that was within ten rings of the pith. The remainder of each stem's wood was used to make up the balance of the kiln charge.

The kiln schedule for white oak used for this study contained nine steps. The kiln samples were six pieces of bur oak of equal width and length (4" x 96`). Each of the six pieces was marked into sections (4" x 8") and numbered. Table 3 shows a graphic representation of how each sample was laid out and numbered. Each row of the table represents a sample board and each column represents a kiln step. The column marked KCS was used to determine when a kiln step change needed to be made.

Table 3. Kiln sample breakdown

<table>
<thead>
<tr>
<th>KCS</th>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
<th>Step 6</th>
<th>Step 7</th>
<th>Step 8</th>
<th>Step 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>T11C</td>
<td>T111</td>
<td>T112</td>
<td>T113</td>
<td>T114</td>
<td>T115</td>
<td>T116</td>
<td>T117</td>
<td>T118</td>
<td>T119</td>
</tr>
<tr>
<td>T12C</td>
<td>T121</td>
<td>T122</td>
<td>T123</td>
<td>T124</td>
<td>T125</td>
<td>T126</td>
<td>T127</td>
<td>T128</td>
<td>T129</td>
</tr>
<tr>
<td>T13C</td>
<td>T131</td>
<td>T132</td>
<td>T133</td>
<td>T134</td>
<td>T135</td>
<td>T136</td>
<td>T137</td>
<td>T138</td>
<td>T139</td>
</tr>
<tr>
<td>T21C</td>
<td>T211</td>
<td>T212</td>
<td>T213</td>
<td>T214</td>
<td>T215</td>
<td>T216</td>
<td>T217</td>
<td>T218</td>
<td>T219</td>
</tr>
<tr>
<td>T22C</td>
<td>T221</td>
<td>T222</td>
<td>T223</td>
<td>T224</td>
<td>T225</td>
<td>T226</td>
<td>T227</td>
<td>T228</td>
<td>T229</td>
</tr>
<tr>
<td>T23C</td>
<td>T231</td>
<td>T232</td>
<td>T233</td>
<td>T234</td>
<td>T235</td>
<td>T236</td>
<td>T237</td>
<td>T238</td>
<td>T239</td>
</tr>
</tbody>
</table>

¹KCS - Kiln Control Samples.
Kiln Schedule

The kiln drying schedule used in this study was taken from the Dry Kiln Operator's Manual (p. 153). This manual was written by the Forest Products Laboratory (FPL) at Madison, Wisconsin, for the United States Forest Service, a branch of the United States Department of Agriculture. The kiln schedule is shown in Table 4.

Table 4. Drying schedule for 4/4 white oak (based on T4-C2)

<table>
<thead>
<tr>
<th>Step No.</th>
<th>% M.C.</th>
<th>Dry Bulb Temp. °F</th>
<th>Wet Bulb Temp. °F</th>
<th>Wet Bulb Dep. °F</th>
<th>R.H. %</th>
<th>EMC %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>&gt;40</td>
<td>110</td>
<td>106</td>
<td>4</td>
<td>87</td>
<td>17.5</td>
</tr>
<tr>
<td>2.</td>
<td>40</td>
<td>110</td>
<td>105</td>
<td>5</td>
<td>84</td>
<td>16.2</td>
</tr>
<tr>
<td>3.</td>
<td>35</td>
<td>110</td>
<td>102</td>
<td>8</td>
<td>75</td>
<td>13.3</td>
</tr>
<tr>
<td>4.</td>
<td>30</td>
<td>120</td>
<td>106</td>
<td>14</td>
<td>62</td>
<td>10.0</td>
</tr>
<tr>
<td>5.</td>
<td>25</td>
<td>130</td>
<td>100</td>
<td>30</td>
<td>35</td>
<td>5.6</td>
</tr>
<tr>
<td>6.</td>
<td>20</td>
<td>140</td>
<td>90</td>
<td>50²</td>
<td>14</td>
<td>2.6</td>
</tr>
<tr>
<td>7.</td>
<td>15</td>
<td>180</td>
<td>130</td>
<td>50²</td>
<td>26</td>
<td>3.3</td>
</tr>
<tr>
<td>8.</td>
<td>Eq.³ 10%</td>
<td>180</td>
<td>162</td>
<td>18</td>
<td>65</td>
<td>8.1</td>
</tr>
<tr>
<td>9.</td>
<td>Cond.⁴</td>
<td>180</td>
<td>175</td>
<td>5</td>
<td>89</td>
<td>14.5</td>
</tr>
</tbody>
</table>

¹Depression
²Close control of wet-bulb temperature not necessary.
³Equalization.
⁴Condition only if casehardening detected.
Drying Process and Data Acquisition

The drying process followed in this study was as follows. The initial moisture content for each kiln control sample was determined by ovendrying a small portion of each kiln sample at 103° C (plus or minus 2°) until a constant weight was achieved. The initial moisture content was then determined as follows:

\[
% \text{ Moisture Content} = \frac{\text{Green Weight} - \text{Ovendry Weight}}{\text{Ovendry Weight}} \times 100
\]

The kiln control samples (KCS), which were previously listed in Table 3, were weighed and the moisture content was calculated to determine when each kiln step change needed to be made. For the first seven kiln steps, the kiln samples appropriate to a kiln step were dried according to the parameters established in the kiln schedule.

A "C" program was written for a DOS based computer that was used for control and data acquisition. Figure 8 shows a block diagram of the equipment used for data acquisition in the study.

A Tektronix digital storage oscilloscope with a thermal printer provided the means to monitor visually and to produce a hard copy of AE events. A laminated polyvinylidene fluoride (PVDF) 28 µm sensor, 70 mm x
Figure 8. Block diagram of computer and data acquisition equipment
15 mm, was attached to the end grain of each sample using cyanoacrylate adhesive. The wood surface was machined with an eighty-tooth, carbide-tipped combination blade. The sensor was clamped to the wood surface using a 12" parallel clamp and a surface ground steel flat 0.25" x 1.25" x 4". The steel flat was used to equalize the clamping pressure to distribute evenly the adhesive between the sensor and the wood.

The sensors were then connected to amplifiers, which increased the magnitude of signals produced by the PVDF sensor 100,000 times. The multiplexer, controlled by the computer, then chose the appropriate sample's signals to send to the filter, which had a band pass between 60KHz and 11KHz. After passing through the filter, the signals were counted and stored in the data file. As the wood samples were dried, they were monitored for acoustic emissions. The computer data acquisition program monitored acoustic emission rates for each of the six samples for one minute. The program then recorded the number of AE events, the temperature (°F), and the relative humidity.

When a kiln step had been completed, those samples used in the step (e.g., for step 1, samples T111 through T231) were removed from the kiln.

Each sample was examined immediately with a stereo microscope on all exterior surfaces to count the number of surface and end checks present.

The slice technique developed at the Forest Products Laboratory was used to determine the amount of stress. As each slice sample was divided
into equal-interval sections for the slice test, it was also examined for tissue rupture, honeycomb, and collapse.

Kiln steps eight and nine were done to complete the drying of the kiln charge. The eighth kiln step was an equalizing procedure to bring the pieces within the kiln charge to within 2% MC of one another. The kiln charge was equalized to 9% moisture content.

At the end of the equalizing procedure, the KCS were checked for casehardening using the prong test, which visually determines the presence and severity of casehardening. Since no casehardening was found based on prong test results, kiln step nine was not needed. The drying experiment was then complete and the kiln was shut down.

Pretest

To determine if AE events actually were being monitored by the sensors or if electromagnetic interference was being monitored, a series of pretests were conducted prior to the actual experiment. One sensor was attached to a wood sample and the other sensor was sheltered so as not to be affected by air movement in the kiln. Both the sheltered sensor and the wood sample with the attached sensor were placed in the kiln and dried. The drying conditions were set to a dry-bulb temperature of 140° F and a wet-bulb temperature of 90° F. Each sensor was monitored for fifteen seconds and information was recorded. Each pretest lasted for a period of
thirty minutes. The pretest was repeated ten times at various times during the day and on several different days. At the same time the computer was recording activity produced by the sensors, the information was displayed on a Tektronix TDS320 two-channel digital storage oscilloscope.

The wave forms produced were examined to compare the activity coming from the two sensors. The information monitored from the wood sample showed AE events with noise in between AE events while the sheltered sample showed only noise.

It was found that the building housing the dry kiln (Bessey Hall at Iowa State University) had much higher levels of electromagnetic interferences during the day than in the evening. To insure that electromagnetic interference did not cause erroneous readings, data were only collected from 7:00 p.m. to 7:00 a.m.

Data Analysis

Upon completion of the data acquisition, the information was analyzed to answer the research questions and test the hypotheses. The variables were described in terms of mean responses and standard deviations.

The analysis of variance (ANOVA) procedure was computed to test whether the observed differences in group means could be reasonably attributed to chance, or whether to suspect that a statistical difference
existed between acoustic emission rates categorized by kiln steps one through seven. The ANOVA procedure requires the following three assumptions:

1. Each group must be an independent and random sample.
2. The populations from which the samples are taken are normally distributed.
3. In the population, the variances of the groups are equal.

Bartlett's test for homogeneity of variance was used to test whether the variances of the groups were equal (Borg & Gall, 1989; Hinkle, 1988).

The ANOVA procedure does not pinpoint which groups are statistically different from each other, but it does indicate that there is a difference. If a statistical difference was found, a post hoc multiple comparison test was used to identify which groups were statistically different. The Scheffe post hoc test was used to identify statistical differences between groups.

Research question one (What does a typical acoustic emission event look like when a polyvinylidene fluoride sensor is used as an acoustic emission sensor?) was addressed by presenting a printout of an AE event captured by a digital storage oscilloscope.

Research question two (What are the characteristic acoustic emission rates for the first seven kiln steps within the drying schedule?) was addressed by reporting descriptive statistics and by creating a statistical
process control chart for each kiln step based on the AE response rate.

Research question three (What are the stress/strain characteristics for the first seven kiln steps within the drying schedule?) was answered by creating a graph for each kiln step based on the slice test data.

Research question four (What are the characteristic tissue rupture rates for the first seven kiln steps within the drying schedule?) was addressed by examining the samples with a stereo microscope at the end of each kiln step.

Research question five (What are the characteristic collapse rates for the first seven kiln steps within the drying schedule?) was addressed by visually examining the samples for collapse at the end of each kiln step.

Research question six (Does a relationship exist between acoustic emission rate and tissue rupture?) was addressed by examining the samples with a stereo microscope at the end of each kiln step.

Research question seven (Does a relationship exist between acoustic emission rate and casehardening?) was addressed by administering the prong test to each sample at the end of each kiln step.

Research question eight (Does a relationship exist between acoustic emission rate and collapse?) was addressed by visually examining the samples for collapse at the end of each kiln step.

Research hypothesis one (There is no significant difference between mean acoustic emission rates for the first seven kiln steps within the kiln
schedule.) was addressed through the one-way analysis of variance (ANOVA) procedure at an alpha level of 0.05.

Research hypothesis two (No relationship exists between casehardening and acoustic emission rate.) was addressed by examining the relationship between the amount of casehardening and the acoustic emission rate.

Research hypothesis three (No relationship exists between tissue rupture and acoustic emission rate.) was addressed by examining the relationship between the amount of tissue rupture and acoustic emission rate.

Research hypothesis four (No relationship exists between collapse and acoustic emission rate.) was addressed by examining the relationship between the amount of collapse and the acoustic emission rate.

The independent variable in this study was the kiln schedule with seven levels of treatment (kiln drying conditions). The dependent variables in the study were acoustic emission, tissue rupture, casehardening and collapse.
CHAPTER IV: ANALYSIS OF DATA

In this chapter the research questions and hypotheses will be presented in terms of the data acquired through the drying experiment. The results will be presented through the use of narrative, tables, and figures.

Research Questions and Hypotheses

To provide continuity the research questions and hypotheses will be addressed in the order stated previously in Chapter I.

Research question one

What does a typical acoustic emission event look like when a polyvinylidene fluoride sensor is used as an acoustic emission sensor?

A typical AE event is shown in Figure 9. This AE was recorded at random using a digital storage oscilloscope with a printer connected to produce a hard copy. The figure is an actual printout of the oscilloscope screen. The large wave in the center that decays with time to the right is the AE event. The short wave formed on either side of the AE is random noise.

The oscilloscope was set up with each vertical division representing 500 millivolts (mv) and each horizontal division representing 50 microseconds (μs). The AE wave form had a maximum amplitude of 1400mv, and its duration lasted approximately 80 μs.
The data acquisition equipment was set to count AE events when any portion of the AE event went above 870mv. This waveform resulted in a count of four being recorded by the data acquisition equipment. In other words, any spike within the AE event that went above a positive 870mv was counted. The counter voltage in this study was set at 870mv to insure that random noise or electromagnetic interference would not be recorded as AE events.

Research question two

What are the characteristic acoustic emission rates for the first seven kiln steps within the drying schedule?
The acoustic emission summary statistics for each of the seven kiln steps are shown in Table 5. The data shown in the table depicts the AE rate per minute. A wide range is shown between the AE mean rates for each kiln step and between standard deviations for each kiln step.

Table 5. Summary statistics for the seven kiln steps' acoustic emission rates

<table>
<thead>
<tr>
<th>Kiln Step Number</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step One</td>
<td>107.05</td>
<td>147.97</td>
</tr>
<tr>
<td>Step Two</td>
<td>56.61</td>
<td>91.65</td>
</tr>
<tr>
<td>Step Three</td>
<td>102.50</td>
<td>124.30</td>
</tr>
<tr>
<td>Step Four</td>
<td>308.91</td>
<td>346.60</td>
</tr>
<tr>
<td>Step Five</td>
<td>47.62</td>
<td>137.51</td>
</tr>
<tr>
<td>Step Six</td>
<td>234.02</td>
<td>281.23</td>
</tr>
<tr>
<td>Step Seven</td>
<td>.57</td>
<td>.73</td>
</tr>
</tbody>
</table>

Statistical process control (SPC) charts showing the acoustic emission rates for the first seven kiln steps were generated. A x-bar chart and a s chart are presented for each step. In step four's x-bar chart, it is important to note that point thirty-two would appear to be outside the three sigma limit, but when the actual data were examined, this was not the case. The seven pairs of charts were examined for a stable process based on the following four rules that are known as the Western Electric Zone Tests:
1. A lack of control is indicated whenever a single point falls outside the (three-sigma) control limits.

2. A lack of control is indicated whenever at least two out of three successive values fall on the same side of, and more than two sigma units away from, the central line.

3. A lack of control is indicated whenever at least four out of five successive values fall on the same side of, and more than one sigma unit away from, the central line.

4. A lack of control is indicated whenever at least eight successive values fall on the same side of the central line (Wheeler & Chambers, 1992, p. 96).

Figures 10, 13, 15, and 16 (step one, step four, step six, and step seven) all show control charts that do not violate any of the four rules. In examining Figure 11, step two's x-bar chart shows two circled points out of control, violating rule two. The s chart shows five circled points out of control, violating rule one.

In examining Figure 12, step three's x-bar chart shows three circled points out of control, violating rule two. The s chart shows two circled points out of control, violating rule two.

In examining Figure 14, step five's x-bar chart shows four circled points out of control, violating rule three.
Figure 10. Step one x-bar and s control chart
Figure 11. Step two x-bar and s control chart
Figure 12. Step three x-bar and s control chart
Figure 13. Step four x-bar and s control chart
Figure 14. Step five x-bar and s control chart
Figure 15. Step six x-bar and s control chart
Figure 16. Step seven x-bar and s control chart
Research question three

What are the stress/strain characteristics for the first seven kiln steps within the drying schedule?

The method used to report stress/strain within a step is based on the slice test. Figure 17 depicts the slice test strain for each of the seven kiln steps, and Figure 18 depicts the associated moisture content for each slice within a step. Slices 1 and 7, 2 and 6, and 3 and 5 were paired together and then averaged to produce the graph in Figure 17. An examination of Figure 17 shows the following. In steps one through three the shell slices (1, 2, 6, 7) are in tension and the core slices (3-5) are in compression. In steps four and five the shell slices (1 and 7) are reduced in tension and the core slices (3 and 5) have reversed and are in tension while slice 4 has reduced in compression. In steps six and seven there has been a complete reversal with the shell now in compression and the core in tension.

In examining Figure 18, the seven kiln steps' shell slices show a reduction in moisture content as the drying process progresses while the core slices always show a higher moisture content than the shell. Progressing from step number one to step number seven the difference between shell moisture content and core moisture content becomes less and less.

As stated previously, the kiln drying schedules are designed to reduce
Figure 17. Slice test strain for the seven kiln steps.
Figure 18. Slice test of moisture content for the seven kiln steps
drying degrade to a minimum. The wood used in this study dried with very little degrade.

**Research question four**

What are the characteristic tissue rupture rates for the first seven kiln steps within the drying schedule?

As a result of the tests that were carried out at the end of each kiln step, no measurable amounts of tissue rupture were found. For this reason, any further discussion would be inappropriate due to the lack of data.

**Research question five**

What are the characteristic collapse rates for the first seven kiln steps within the drying schedule?

As a result of the tests that were carried out at the end of each kiln step, no measurable amounts of collapse were found. For this reason, any further discussion would be inappropriate due to the lack of data.

**Research question six**

Does a relationship exist between acoustic emission rate and tissue rupture?
As a result of the tests that were carried out at the end of each kiln step, no measurable amounts of tissue rupture were found. For this reason, any further discussion would be inappropriate due to the lack of data.

Research question seven

Does a relationship exist between acoustic emission rate and casehardening?

As a result of the tests that were carried out at the end of each kiln step, no measurable amounts of casehardening were found. For this reason, any further discussion would be inappropriate due to the lack of data.

Research question eight

Does a relationship exist between acoustic emission rate and collapse?

As a result of the tests that were carried out at the end of each kiln step, no measurable amounts of collapse were found. For this reason, any further discussion would be inappropriate due to the lack of data.
Research hypothesis one

There is no significant difference between mean acoustic emission rates for the first seven kiln steps within the kiln schedule.

To determine if there was a difference between the seven kiln steps' acoustic emission rates the different kiln steps were compared using the one-way analysis of variance procedure. In addition, if a significant F ratio was found using the one-way ANOVA procedure, the Scheffe multiple range comparison test was used to identify which groups were different from each other.

The test of hypothesis one yielded a significant F ratio of 258.7 (p = .0000) at the .05 alpha level, rejecting the null hypothesis that the groups' acoustic emissions rates were equal.

The Scheffe multiple range comparison test identified which steps were significantly different from the others. Nineteen differences were found and reported in Table 6, which shows the results of the one-way ANOVA and the Scheffe procedure. The data were examined using histograms to check for normality. It was found that the data were skewed in each of the seven kiln steps. Bartlett's test was run to determine if the homogeneity of variance assumption for the one-way ANOVA procedure was violated. A significant F ratio equal to 1844 (P = .000) was returned. Thus it was
Table 6. One-way ANOVA and Scheffe contrasts for the variable acoustic emission rate for the seven kiln steps

<table>
<thead>
<tr>
<th>Variable/Source</th>
<th>D.F.</th>
<th>Sum of Squares</th>
<th>Mean Squares</th>
<th>F Ratio</th>
<th>Prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between Grs.</td>
<td>6</td>
<td>59770332</td>
<td>9661722</td>
<td>258.7</td>
<td>.0000**</td>
</tr>
<tr>
<td>Within Grs.</td>
<td>5615</td>
<td>216213350</td>
<td>38506</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5621</td>
<td>275983682</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Scheffe Multiple Range Comparison Test

<table>
<thead>
<tr>
<th>Mean AE</th>
<th>Kiln Step Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.57</td>
<td>7  5  2  3  1  6  4</td>
</tr>
<tr>
<td>47.62</td>
<td>*</td>
</tr>
<tr>
<td>56.61</td>
<td>*</td>
</tr>
<tr>
<td>102.50</td>
<td>*  *</td>
</tr>
<tr>
<td>107.05</td>
<td>*  *</td>
</tr>
<tr>
<td>234.02</td>
<td>*  *</td>
</tr>
<tr>
<td>308.91</td>
<td>*  *</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 level.

determined that the kiln step groups come from populations with different variances. This violates the homogeneity of variance assumption. For these reasons, the results of the one-way ANOVA procedure should be viewed with caution. When the means were compared visually for each of the seven kiln steps, large differences did exist. These differences support the alternative hypothesis that the mean acoustic emission rates were not the same for all
seven kiln steps.

As stated previously, the kiln drying schedules are designed to reduce drying degrade to a minimum. The wood used in this study dried with very little degrade. No measurable amounts of tissue rupture, collapse, or casehardening as determined by the prong test could be found. The lack of tissue rupture, collapse, and casehardening was not expected and is very atypical of usual drying outcomes.

**Research hypothesis two**

No relationship exists between casehardening and acoustic emission rate.

No measurable amounts of defects were found; therefore, any further discussion would be inappropriate due to the lack of data.

**Research hypothesis three**

No relationship exists between tissue rupture and acoustic emission rate.

No measurable amounts of defects were found; therefore, any further discussion would be inappropriate due to the lack of data.
Research hypothesis four

No relationship exists between collapse and acoustic emission rate.

No measurable amounts of defects were found; therefore, any further discussion would be inappropriate due to the lack of data.
CHAPTER V: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The preceding four chapters of this study dealt with the introduction, review of literature, methodology, and analysis of data of the study. Chapter V summarizes the previous chapters, draws conclusions, and makes recommendations.

Summary

The central purpose of this study was to determine if an in-kiln monitoring system based on the acoustic emission rates of wood as it dries could be developed to monitor the traditional kiln drying process.

More specifically, this study addressed the following research questions and research hypotheses and presented the appropriate results.

Research question one

What does a typical acoustic emission event look like when a polyvinylidene fluoride sensor is used as an acoustic emission sensor?

A typical acoustic emission event is shown in Figure 19. The waveform was captured with a digital storage oscilloscope with a printer attached. The AE event was recorded at random. Any time a spike in the waveform went above the counter threshold voltage of 870 millivolts the
Figure 19. Typical acoustic emission wave form

spike was recorded as an AE. The wave form in Figure 19 shows that four spikes were counted for the acoustic emission because they went above the threshold voltage.

Research question two

What are the characteristic acoustic emission rates for the first seven kiln steps within the drying schedule?

A summary of the descriptive statistics for research question two is shown in Table 7.
Table 7. Summary statistics for the seven kiln steps' acoustic emission rates

<table>
<thead>
<tr>
<th>Kiln Step Number</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step One</td>
<td>107.05</td>
<td>147.97</td>
</tr>
<tr>
<td>Step Two</td>
<td>56.61</td>
<td>91.65</td>
</tr>
<tr>
<td>Step Three</td>
<td>102.50</td>
<td>124.30</td>
</tr>
<tr>
<td>Step Four</td>
<td>308.91</td>
<td>346.60</td>
</tr>
<tr>
<td>Step Five</td>
<td>47.62</td>
<td>137.51</td>
</tr>
<tr>
<td>Step Six</td>
<td>234.02</td>
<td>281.23</td>
</tr>
<tr>
<td>Step Seven</td>
<td>.57</td>
<td>.73</td>
</tr>
</tbody>
</table>

X-bar and s statistical process control charts were generated for each of the seven kiln steps. Steps one, four, six, and seven had control charts that showed a normal drying process. Steps two, three, and five had control charts that indicated an out-of-control drying process.

Research question three

What are the stress/strain characteristics for the first seven kiln steps within the drying schedule?

The stress/strain characteristics for the drying process were found to be as follows:

1. Early in the drying process a buildup of tensile stress in the
shell and a buildup of compressive stress in the core occurred.

2. Midway through the drying process the shell reversed to compressive stress and the core reversed to tensile stress.

3. Late in the drying process the shell showed an increase in compressive stress and the core showed an increase in tensile stress.

Research hypothesis one

There is no significant difference between mean acoustic emission rates for the first seven kiln steps within the kiln schedule.

To determine if there was a significant difference between the acoustic emission rates between the seven kiln steps the one-way analysis of variance (ANOVA) was used. If a significant F ratio was returned, the Scheffe post hoc comparison procedure was used to identify which groups were different.

A significant F value of 258.7 \( (P = .0000) \) was returned at the .05 level, rejecting the null hypothesis that the groups’ mean acoustic emission rates were equal. The Scheffe post hoc procedure identified nineteen differences between the seven kiln steps. The ANOVA assumptions of normality and homogeneity of variance were violated. For this reason, the results of the one-way ANOVA should be viewed with caution. When the
means were examined visually, large differences existed, supporting the alternative hypothesis that the kiln step mean acoustic emission rates differed between the kiln steps.

Following the kiln drying schedule developed by the Forest Products Laboratory, the wood used in this study (bur oak, *Quercus macrocarpa* Michx.) dried with very little degrade. No measurable amounts of tissue rupture, collapse, or casehardening as determined by the prong test could be found. Therefore, any further discussion of research questions four through eight and research hypotheses two through four would be inappropriate due to the lack of data.

Discussion

The present hardwood drying process is one of compromise between manufacturing costs and the amount of acceptable drying degrade. Long, slow drying times produce better quality wood but incur higher costs. Short, fast drying times reduce drying costs but also reduce the wood quality. The problem then becomes one of producing high quality at a reasonable operating cost.

If drying conditions can be controlled to allow tensile and compressive forces to build to a point just below the ultimate stress of the wood, drying degrade in the form of tissue rupture can be drastically reduced while maintaining the fastest possible drying rate. Present drying schedules do
not have the ability to control the drying process to such an extent because they are based on a compromise between time and degrade and not on continuous monitoring.

This study sought to improve this compromise by developing an in-kiln monitoring system based on the acoustic emission rates of wood as it dries. Through the use of polyvinylidene fluoride (PVFD) film and statistical process control (SPC), it was possible in this study to monitor the drying of bur oak. This was one of the first studies done in a commercial kiln that allowed real-world drying problems to be encountered and that recorded their effects through the use of AE monitoring.

AE events produced as a result of the wood drying process are precursors to visible drying degrade. The problem is one of measuring the AE information and then understanding the information. Polyvinylidene fluoride (PVFD) provides the means to measure AE information, and statistical process control (SPC) provides the means to interpret the information.

Present day hardwood kiln schedules should continue to be the basis for the drying of hardwood. The interaction of temperature, humidity, and air velocities in one kiln step can have adverse effects in later kiln steps. Present kiln schedules control this type of problem. While controlling this type of problem is a positive feature of the kiln schedules, on the negative side they also allow for certain levels of drying degrade. Drying schedules
use the difference between wet-bulb and dry-bulb temperatures to control the drying process in the kiln. The kiln operator monitors the moisture content of the kiln charge and adjusts the dry-bulb and wet-bulb temperatures when a kiln step change is determined. The kiln operator does not have the means to determine if the drying process should be increased for short periods to reduce total drying time or if the drying process should be slowed to reduce tissue rupture within a given kiln step.

As investigated by this study, using SPC to interpret AE information provides the means for the kiln operator to refine the kiln steps within a kiln schedule to reduce drying degrade. These kiln step refinements need to be modified during each kiln load because each load has numerous variables that affect the drying process. The information produced by the wood itself through acoustic emissions is used to take into account all the variables so that each kiln load is dried according to its individual characteristics.

This study found that the drying process could be monitored in real time using AE monitoring and using SPC to interpret the AE information. This study made no attempt to adjust the drying process based on AE activity. The purpose of the study was to determine if AE information could be monitored and interpreted. It is clear that using AE information interpreted by SPC provides the kiln operator the means through computer control to adjust the drying process in real time to increase dried wood quality and reduce drying costs.
Limitations

The following limitations apply to this study.

(1) Dry-bulb and wet-bulb temperatures were measured by standard industry equipment and not digital readout equipment.

(2) Data acquisition was limited to the clock speed of the equipment.

(3) The kiln had to be opened periodically to remove the samples in order to measure the moisture content.

(4) The filter was limited to a maximum range of 111 KHz.

Conclusions

The researcher made the following conclusions based on the results of the data presented in Chapter IV.

(1) The use of polyvinylidene fluoride film is a viable material to use as an acoustic emission sensor in the wood drying process. Acoustic emission rates were monitored and recorded for the first seven kiln steps.

(2) Kiln schedules are designed to limit tissue rupture in the drying process but also to allow for a degree of casehardening to occur. Casehardening stress can be relieved by the conditioning process and is thus allowed in the drying schedules. Although compressive and tensile stresses were identified by the slice test, the stresses were not great enough to induce casehardening. When the prong test was performed on the kiln samples, no casehardening was found. The bur oak used in this study
dried atypically from what was anticipated.

(3) In the manufacture of lumber, the drying process is the single most costly step in terms of energy, time, and material loss. A reduction in the drying time and/or an increase in the quality of the dried lumber offer potential for large economic gains (Gui, Jones, Taylor, & Issa, 1994). The combination of using acoustic emissions to monitor the wood drying process and interpreting those acoustic emissions by statistical process control charts can be used as a means to adjust the drying process in real time to increase quality and possibly to reduce energy consumption.

(4) Acoustic emission monitoring of the wood drying process is much like trying to understand a coded message. Without the proper code it is impossible to decipher the messages. Statistical process control charts are powerful tools for detecting uncontrolled variation and are effective with virtually any type of data (Shewhart, 1931; Shewhart & Deming, 1939; Wheeler & Chambers, 1992).

The use of control charts provides the means to understand what the acoustic emissions are saying about the drying process. The control charts for kiln steps two, three, and five show an out-of-control drying process. Once an out-of-control process is identified, the cause can be identified and adjustments can be made to the process. One possible cause for kiln steps two, three, and five being out-of-control was a fluctuating or unstable relative humidity control.
This study was not intended to identify the cause of the variations. However, it was important to this study to identify that a problem existed in kiln steps two, three, and five. The existence of a problem could not have been identified without the use of acoustic emission monitoring and SPC.

(5) This study was conducted in a 500 board foot commercial kiln. The wood was dried using a kiln schedule for white oak taken from the Dry Kiln Operator's Manual. Previous studies were done using equipment designed for laboratory use. Also, previous studies did not use the drying schedules based on the industry standard presented in the Dry Kiln Operator's Manual. This study represents one of the first attempts to study acoustic emission events in a commercial kiln using an industrial kiln schedule.

(6) Based on the results of the one-way analysis of variance procedure and the Scheffe post hoc multiple comparison procedure, nineteen differences were found between various kiln steps. The data violated two of the three assumptions of the one-way ANOVA, normality and homogeneity of variance. For this reason, the results of the one-way ANOVA should be viewed with caution. When the means of the seven kiln steps were examined, differences clearly existed. Five thousand six hundred and twenty-two data points were recorded and were divided almost evenly among the seven kiln steps.

The large sample size lends support to the alternative hypothesis that
there are differences between acoustic emission rates for the seven kiln steps. Clearly the kiln conditions (temperature, humidity, and air flow) in each step cause different rates of acoustic emissions to occur.

Recommendations for Further Research

Based on the findings and conclusions of this study, the following recommendations for further research are presented.

(1) As a result of this study, it was found that three of the kiln steps reported uncontrolled variations in the drying process as evidenced by the statistical process control charts. An area that should be studied further to determine its effect on the variations is the method of attachment of the sensors to the wood.

(2) The study should be repeated using the latest innovations in data acquisition equipment and a filter that can be adjusted to allow passage of a broader bandwidth of frequencies.

(3) This study was conducted using bur oak, which is a ring porous hardwood. A semi-ring porous wood and a diffuse porous wood should be studied to compare their acoustic emission patterns to those made by bur oak.

(4) A study should be conducted in which tissue rupture, casehardening, and collapse are induced into the kiln steps to determine how they relate to acoustic emission.
(5) A study should be conducted to investigate the effect of humidity on acoustic emissions. It is well documented that humidity has an effect on acoustic emission events, but further study is needed to determine the degree of relative humidity change that results in a change in the acoustic emission rate.

(6) A study should be conducted to assess the feasibility of using an electronic circuit designed on the principles of common mode rejection of electromagnetic interference to measure the acoustic emission rates produced during the wood drying process.
REFERENCES


