ACOUSTIC EMISSION BASED
CONTROL OF WOOD DRYING

by

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(ABSTRACT)

Drying is one of the most critical process steps in converting trees to a marketable material for use in high value wood products. The primary reasons for drying wood are to prevent biological deterioration and to improve mechanical strength and dimensional stability. The purpose of this research study was to develop an approach to the control of drying red oak lumber that monitors acoustic emission as the basis for setting environmental conditions throughout the drying process. Northern red oak (*Quercus* sp.) was chosen for this study because it is one of the more difficult woods grown in the United States to dry without inducing defects. This study was limited to end drying of short lengths of full sized red oak lumber.

An automated system of computer based hardware and software was designed and used to demonstrate the fundamental elements needed to control drying based on acoustic emission. These are short bursts of energy released by small fractures from a material under stress. It was observed that the rate of acoustic emission indicates the rate of checking damage resulting from drying induced stresses. The rate of acoustic emission was found to range over several orders of magnitude for rates of wood damage that ranged from insignificant to severe. Commercial instrumentation was found to be capable of
detecting acoustic emission from wood without significant interference from extraneous sources. It was also found to be feasible to monitor changes in wood sound attenuation that would alter the interpretation of the acoustic emission data. The rate of acoustic emission was found to respond with basically second-order dynamics to changes in drying conditions. The time response to large-step changes in drying conditions was found to be on the order of minutes while the response to small-step changes was found to be on the order of many hours with a period of oscillation of about 60 hours. As an aid to optimizing the control process, the underlying physics of this dynamic response was modeled with an analogous electrical circuit and the associated differential equation. Finally, closed loop control of the drying process based on the rate of acoustic emission was demonstrated.
Acknowledgements

I would like to express my sincere appreciation to a number of helpful people who have made significant contributions to this project. First and foremost, C. Skaar, who initiated the acoustic emission project and provided leadership throughout the investigation. Without his exceptional dedication, as a scientist and as an educator, completion of this document would not have been possible. I am also indebted to P. E. Field, E. G. Henneke, F.M. Lamb, W. C. Thomas, and G. M. Wengert, who served on my committee and provided useful and willing guidance in their respective areas of expertise. I would also like to express appreciation to several additional people for their help.

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Colleagues at Bell Labs were very helpful; W. Strauss suggested the Lagrangian as a method of developing a differential equation to describe the dynamics of the wood drying system, N. Zeisue and F. Dickens shared their understanding of resonance, and H. Sidei provided valuable discussions of non-linear dynamic systems.

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<th>Meaning</th>
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<tr>
<td>$A$</td>
<td>Cross sectional area of sample</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Area through which heat conducts</td>
</tr>
<tr>
<td>$A_f$</td>
<td>Area through which water flows</td>
</tr>
<tr>
<td>$A_s$</td>
<td>Surface area of wood</td>
</tr>
<tr>
<td>$b$</td>
<td>Thickness of sample</td>
</tr>
<tr>
<td>$C$</td>
<td>Celsius</td>
</tr>
<tr>
<td>$D$</td>
<td>Moisture diffusion coefficient</td>
</tr>
<tr>
<td>$D_{gl}$</td>
<td>Diffusion coefficient of gross wood in longitudinal direction</td>
</tr>
<tr>
<td>$e$</td>
<td>Base of natural logarithm</td>
</tr>
<tr>
<td>$e_n$</td>
<td>Controller error at time interval $n$</td>
</tr>
<tr>
<td>$E$</td>
<td>Modulus of elasticity</td>
</tr>
<tr>
<td>$E_{c. v.}$</td>
<td>Total energy storage within the control volume</td>
</tr>
<tr>
<td>$E_g$</td>
<td>Energy released during microcrack growth</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$G$</td>
<td>Specific gravity of wood at given moisture content</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>$G_D$</td>
<td>Controller gain, derivative term</td>
</tr>
<tr>
<td>$G_I$</td>
<td>Controller gain, integral term</td>
</tr>
<tr>
<td>$G_P$</td>
<td>Controller gain, proportional term</td>
</tr>
<tr>
<td>$h$</td>
<td>Half the wide dimension of wood sample</td>
</tr>
<tr>
<td>$h_c$</td>
<td>Convective heat transfer coefficient</td>
</tr>
<tr>
<td>$h_e$</td>
<td>Enthalpy of water mass exiting the control volume as a saturated vapor</td>
</tr>
<tr>
<td>$h_f$</td>
<td>Enthalpy of a saturated liquid</td>
</tr>
<tr>
<td>$h_{fg}$</td>
<td>Heat of vaporization</td>
</tr>
<tr>
<td>$I$</td>
<td>Moment of inertia of sample</td>
</tr>
<tr>
<td>$k$</td>
<td>Function describing parabolic load that bends wood fibers at ends</td>
</tr>
<tr>
<td>$k_c$</td>
<td>Thermal conductivity</td>
</tr>
<tr>
<td>$K_{cond}$</td>
<td>Moisture conductivity coefficient</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of wood moisture gradient</td>
</tr>
<tr>
<td>$L$</td>
<td>For a system, the time-dependent energy storage minus the time-independent energy storage, called the Lagrangian</td>
</tr>
<tr>
<td>$m$</td>
<td>Moisture content of the wood, kilograms of water per kilogram of wood</td>
</tr>
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*List of Symbols*
<table>
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<th>Symbol</th>
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<tr>
<td>( \dot{m} )</td>
<td>Rate of water mass flow from the control volume, per kilogram of wood</td>
</tr>
<tr>
<td>( \dot{m}_i )</td>
<td>Rate of change in water mass flow rate from the control volume</td>
</tr>
<tr>
<td>( \Delta m )</td>
<td>Difference in moisture content over some length</td>
</tr>
<tr>
<td>( m_{\text{bar}} )</td>
<td>Average moisture content for a moisture gradient</td>
</tr>
<tr>
<td>( m_{\text{wood}} )</td>
<td>Total mass of dry wood within the control volume</td>
</tr>
<tr>
<td>( M )</td>
<td>Total mass of water within the control volume</td>
</tr>
<tr>
<td>( \dot{M} )</td>
<td>Total mass flow rate of water</td>
</tr>
<tr>
<td>( M_e )</td>
<td>Total mass of water vapor that exits control volume</td>
</tr>
<tr>
<td>( M_m )</td>
<td>Bending moment</td>
</tr>
<tr>
<td>( N_c )</td>
<td>Number of counts</td>
</tr>
<tr>
<td>( O_n )</td>
<td>Output from control equation at time interval ( n )</td>
</tr>
<tr>
<td>( \Delta P )</td>
<td>Pressure difference in flow direction</td>
</tr>
<tr>
<td>( q )</td>
<td>Rate of heat transfer</td>
</tr>
<tr>
<td>( Q )</td>
<td>Quality factor for an oscillator</td>
</tr>
</tbody>
</table>

*List of Symbols*
\( Q_{c.v.} \) Total heat flow into the control volume

\( \dot{Q}_{c.v.} \) Rate of heat flow into the control volume

\( S_{dhw,m} \) Slope for linearized differential heat of wetting at moisture content \( m \)

\( s_{max} \) Maximum possible dimensional shrinkage

\( t \) Time

\( t_s \) Sampling time interval for controller

\( T \) Time-dependent mechanism of energy storage in the Langrangian (elastic strain energy)

\( T_{DB} \) Dry Bulb temperature

\( T_s \) Temperature of wood surface

\( T_{WB} \) Wet bulb temperature

\( T_\infty \) Temperature of free stream air

\( u \) Elastic strain energy per kilogram wood

\( u_t \) Thermal internal energy of the water at the given temperature

\( U \) Total elastic strain energy storage within wood fibers which depends on moisture content profile

\( V \) Time-independent mechanism of energy storage in the Langrangian (hygroscopic energy)

_List of Symbols_
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$V^*$</td>
<td>Threshold voltage for acoustic emission detection</td>
</tr>
<tr>
<td>$V(t)$</td>
<td>Output voltage of sensor</td>
</tr>
<tr>
<td>$V_0$</td>
<td>Initial acoustic emission signal amplitude from transducer</td>
</tr>
<tr>
<td>$V_{water}$</td>
<td>Volume of water</td>
</tr>
<tr>
<td>$V_{wood}$</td>
<td>Volume of wood</td>
</tr>
<tr>
<td>$W$</td>
<td>Integral heat of wetting; heat energy that goes into the wood to remove water that is below fiber saturation, and is stored as hygroscopic energy</td>
</tr>
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# List of Acronyms

<table>
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<th>Acronym</th>
<th>Description</th>
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<tr>
<td>A/D</td>
<td>Analog to digital</td>
</tr>
<tr>
<td>AE</td>
<td>Acoustic Emission</td>
</tr>
<tr>
<td>AET</td>
<td>Acoustic Emission Technology Corporation</td>
</tr>
<tr>
<td>CAZ</td>
<td>Commutating Auto-Zero</td>
</tr>
<tr>
<td>CPM</td>
<td>Counts per minute</td>
</tr>
<tr>
<td>EMC</td>
<td>Equilibrium Moisture Content</td>
</tr>
<tr>
<td>EPROM</td>
<td>Erasable Programmable Read Only Memory</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>I/O</td>
<td>Input/Output</td>
</tr>
<tr>
<td>LED</td>
<td>Light emitting diode</td>
</tr>
<tr>
<td>MOR</td>
<td>Modulus of Rupture</td>
</tr>
<tr>
<td>PD</td>
<td>Proportional Derivative</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral</td>
</tr>
<tr>
<td>PID</td>
<td>Proportional Integral Derivative</td>
</tr>
<tr>
<td>PV</td>
<td>Process variable for controller</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead-zirconate-titanate</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>SP</td>
<td>Setpoint for controller</td>
</tr>
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</table>
SWF       Stress Wave Factor
TTL       Transistor Transistor Logic
VIA       Versatile Interface Adaptor
List of Greek Symbols Used

\( \alpha \) Indicates proportionality

\( \gamma \) Decay constant (\( >0 \))

\( \rho_{\text{water}} \) Density of liquid water

\( \rho_{\text{wood}} \) Density of wood

\( \sigma_t \) Tensile stress in tangential direction

\( \tau \) Period of oscillation

\( \omega \) Angular frequency, \( 2\pi f \) (rad/sec)
I. Introduction

Drying is one of the most critical process steps in converting trees to a marketable material for use in high value wood products. All wood intended for indoor use must be dried, but some species present difficult problems that must be overcome in order to achieve drying as rapidly as possible without defects. A great amount of work has been done during the past century to increase understanding of the causes of drying defects and to develop improved methods that would enable manufacturers to avoid such damage while minimizing processing costs. The subject of this research study is an approach to the resolution of problems with drying red oak lumber that uses a novel technique of instrumentation and microcomputer based control.

Red oak (Quercus sp.) was chosen for this study because it is one of the more difficult woods grown in the United States to dry without defects. There are other species of wood around the world that are also difficult to dry. Damage to these woods result from the same types of drying control problems as for the North American hardwoods.

When any material is subjected to excessive stresses it begins to fail in some way. The specifics of the failure depend on many variables such as the material, the type of loading such as static or cyclic, rate of loading, etc. At some point these excessive stresses will result in small microscopic failures in the material. Often these failures are below the surface and are not visible. It has been determined that small microfailures represent points of stress concentration and are essentially the seeds that grow into large cracks. Each of the small microfailures releases some of the energy stored in the elastic strain of the material. The energy propagates through the material as sound
waves. Suitable instrumentation can detect these sound waves and the measurements can then be interpreted to indicate the rate of failures. The burst of sound energy resulting from the release of elastic energy during material failure is called an acoustic emission (AE).

The hypothesis of this dissertation was that if acoustic emission data can be related to degrade, then AE data can be used as a primary feedback variable for control of the hardwood lumber drying process. Supporting this hypothesis were the following objectives to:

1. show that it is feasible to monitor AE in a simulated production environment, and that the instrumentation is sufficiently sensitive to measure AE from wood undergoing an acceptable rate of damage (a low rate of AE resulting from mild drying conditions)
2. investigate the specialized instrumentation, computer control hardware and software required, and to study practical alternatives for measuring essential variables such as sound attenuation
3. show that the rate of AE indicate the rate of damage done in wood resulting from drying stresses and is therefore useful as a feedback signal to control the drying process
4. demonstrate closed-loop control of the drying process based on AE data
5. investigate the system dynamics and underlying physics which are essential for achieving a stable and optimal controller.

It should be noted that this study was limited to end drying defects for red oak lumber.

**Drying of Wood**
The primary reasons for drying wood are to prevent biological deterioration and to improve mechanical strength as well as
dimensional stability. At a moisture content \((m)\) greater than about 20% based on dry weight, woods are subject to degradation by fungi and molds [1]. Activity of these decaying and staining organisms is significant for wood \(m\) above 25% and for temperatures between 4 C (40 F) and 38 C (100 F). Mechanical strength is strongly affected by wood \(m\). The modulus of rupture (MOR) of wood increases by about 4% for every 1% decrease in \(m\) below the fiber saturation point (about 30% \(m\)) [2]. For example, the MOR of dry (12% \(m\)) Northern red oak is 1.7 times that of the wood in the green condition [3].

Shrinkage in wood also occurs below the fiber saturation point. The volumetric shrinkage of red oak is 14% between green and oven dry [4]. Most of this shrinkage \((\frac{2}{3})\) is in the tangential direction with less \((\frac{1}{3})\) in the radial direction. Shrinkage in the longitudinal direction is negligible for normal mature wood. Wood intended for use as furniture must be dried to about 6% to 8% \(m\) to put it in equilibrium with the environment found in most households [5]. Depending on the physical dimensions of wood, the wood species, and the drying environment, a considerable amount of time can be required to dry wood to this equilibrium condition.

Some kinds of wood, such as the pines, can be dried quite quickly and without significant defects. It is not uncommon for a commercial kiln to dry 50 mm (2 inch) thick Douglas-fir from the green condition to 6% \(m\) in 5 to 10 days. Oak wood is much more difficult to process. Commercial dry kiln operations require two months or more to dry 50 mm (2 inch) thick red oak lumber from the green condition to 6% \(m\) [6,7]. It might at first be assumed that if the drying conditions were sufficiently severe that even red oak could be dried quickly. This is correct, however, the properties of red oak prevent this from being practical. Wood shrinks as it dries, the outer layers and ends dry much more rapidly than the center. Since the outside of the wood
dries first, it also shrinks first, resulting in a shrinkage gradient. If this shrinkage gradient is large, then large tensile stresses will be generated in the outer fibers of the wood. These tensile stresses can easily exceed the ultimate tensile strength of the material. The result is slowly developing cracks (called checks) in the outer surface of the wood. If the conditions continue to be severe, the inside of a board can be subjected to such great compression that the inner fibers will collapse. The inside will eventually begin to dry, creating shrinkage gradients within the wood core which can result in a reversal of the stresses and cause internal tensile failures. If the tensile failures are internal to the wood, the failures are call honeycombing. This mode of failure, along with compressive failures, are invisible from the outside of the wood. The damage may not be discovered until the wood is shaped for use in a final product, resulting in significant lost value because of the wasted investment of many processing operations. It is the combination of moisture permeability, mechanical strength, anatomical structure, and elastic properties of some woods such as oak that make them so difficult to dry without defects.

It can be difficult to avoid the above mentioned problems. Drying conditions, both temperature and relative humidity, must be carefully controlled for an extended period of time. Uncontrolled drying conditions can do significant irreversible damage to the wood in a matter of hours. To guarantee that damage will be minimized, the drying conditions would need to be moderate, resulting in greatly extended drying time and therefore high processing costs. Since this approach is prohibitively expensive, the conditions are made more severe, resulting in some damage. The problem is therefore one of optimizing the manufacturing process control. It has been estimated that more than 20 million dollars are lost each year in the value of red oak lumber because of drying induced defects. As previously noted,
there are additional species of wood that are similarly difficult to process. The problem solution lies in the adoption of a sensory feedback that can allow the control system to detect the onset of damage and modify drying conditions in real time so that serious damage is avoided and processing costs are minimized. Investigation of a proposed method to solve this problem is the topic of this thesis.

**Historical Perspective**

The problem of drying wood is of course not a new one. It is one that has been of concern for centuries. The first attempts at drying fine woods without damage began hundreds of years ago when craftsmen would store whole logs in a dry building for a year or longer. The drying conditions were not controlled other than simply keeping the wood out of the weather. The result was wood that was dried without excessive damage but the time required was inordinately long. As the use of woods for furniture became more common, a better method was needed to dry the wood quickly and inexpensively. Efforts became intense around the turn of the 20th century. A number of organizations sponsored research in universities as well as at the U. S. Forest Products Laboratory. The result of this work is the common dry kiln that we have in use today. It consist of insulated buildings with temperature and humidity control. The kilns have fan forced air circulation to enhance water mass transfer from the wood surface to the air. Kilns are commonly heated with steam and the humidity is controlled by injecting live steam into the drying compartment. As mentioned above, the drying environment is adjusted periodically to follow empirical schedules that have evolved over the years. The schedule implementation depends on operators periodically removing "sample boards" from the kiln and weighing them to determine their moisture content, then manually adjusting the drying conditions.

The most commonly used procedure for drying red oak is a result of

*Chapter I Introduction*
years of empirical drying research. The essence of this method is to follow a drying schedule that specifies the dry and wet-bulb temperatures as a function of processing time and moisture content of the wood. The drying schedule, which depends on the size and species of the wood, divides the drying time into a number of periods. During each period the wood is maintained at a constant set of conditions (dry-bulb temperature and relative humidity) until the wood dries to some lower average moisture content. For example, 25 mm (one inch) thick red oak lumber is kept at a dry-bulb temperature of 43 C (110 F) and a relative humidity of 60% for a moisture content of between 35% and 30%. The drying conditions are then changed to a dry-bulb temperature of 49 C (120 F) and a humidity of 31% until the moisture content is below 25%. This is continued in a similar stepwise manner, drying at a rate of no more than 3.8% per day, until the wood moisture content attains the target value of about 8% moisture content [8]. In practice, the moisture content is sampled less than once per day. Since the drying conditions are changed in a stepwise fashion, the conditions are never really optimal for maximum drying rate and minimum damage. Significant damage can occur within hours if for some reason there is a control failure or the conditions are simply too severe for a particular load of wood. Clearly a better method of handling the situation is needed.

Modern Approaches
Changes in kiln drying schedules are based on the m of the wood, usually indicated by sample boards which are measured manually. Some modern kilns are beginning to use load cells to continuously weigh the entire load of wood in order to estimate moisture content. Microcomputer based controllers can use this information to automatically adjust the drying conditions to follow a programmed drying schedule. This automation is better than reliance on manual adjustments but still has shortcomings. A major problem with
weight-based automation is the long time required for a detectable mass of water to evaporate. Considerable damage can still result during this time lag. In other words, measurable damage can easily result from a virtually immeasurable loss of water mass.

The drying control problem has also been approached by creating theoretical models. The goal of such models is to derive an improved drying schedule by applying heat and mass transfer theory to the complex wood structure. This approach causes difficult problems because of the complex structure of wood. First, wood is an anisotropic composite material. Its thermal, mechanical, electrical, acoustical, and moisture permeability properties vary greatly in each of the three structural directions. In addition, because wood is a product of biological growth, the above mentioned properties vary in the radial, tangential, and longitudinal directions as well as from one sample to the next. Two trees can vary significantly in their properties even if they grew nearby each other.

**The Acoustic Emission Approach**

All of the above methods lack a direct feedback of the instantaneous drying stresses which cause tensile failures or checks in the wood. The development of these checks is really the variable of interest for the drying of high value hardwoods. The efforts put into this dissertation are directed toward providing the feedback that is needed to provide optimal wood drying control; a continuous indication of the state of stress in the wood by monitoring AE.

In the remainder of this document the use of AE as an indicator of stress in materials is discussed. First, a review of important background material relevant to wood drying and AE will be given. The experimental apparatus and system electronics used to acquire
data and to implement control strategies during the experimentation will then be discussed. Next, a discussion of experimental results will be given and finally, a model will be presented which describes the system dynamics from the perspective of energy flow in the wood. An understanding of the system dynamics is essential to achieving a stable control loop based on the rate of AE.

Note that this study was focused on end checking. Normally, face checking is the limiting factor in the rate of drying woods such as oak. This study was restricted to end checking because of the small drying chamber that was available. This restriction was not considered a problem since the project focused on the development of a new process, not on an in-depth study of the particular failure mechanisms in wood that limit the rate of drying in a commercial sized kiln.
II. Theory and Literature Review

Wood drying is a complex process that involves convective and conductive heat transfer as well as mass transfer. This chapter begins with a discussion of the energy balance for wood drying including the energy that is stored in the wood in the forms of elastic strain energy and hygroscopic energy. This is followed by some brief notes on the mechanisms of heat transfer that are important to wood drying. Since the measurement of acoustic emission is important to this work, background information is given on this nondestructive material monitoring technique and to some previous AE work that has been done with wood. To complete the discussion of important background topics, automatic control theory is briefly reviewed with particular emphasis on digital PID (proportional-integral-derivative) control by a computer. A summary discussion is then given to show how these various technologies can be combined to improve control of the wood drying process.

Wood Drying Theory

Energy is required to dry wood. Energy in a kiln takes several forms such as electrical power to operate fans and the control system, but the bulk of the energy used is in the form of heat to evaporate water in wood. The heat energy for drying wood is the most expensive portion of operating costs in processing lumber. The rate of wood drying increases with increasing temperature, so wood drying is normally done at temperatures above ambient. Even though a kiln is an insulated structure, much heat energy is lost to the surrounding environment as waste in addition to energy required to evaporate the water from the wood. This lost energy is a significant cost and is a primary motivation for investigating methods to dry wood more quickly.
An energy balance was done on a sample of wood. The control volume was selected to be the volume of wood as shown in Figure 2-1 and the first law of thermodynamics for a control volume was applied [9]. Note that energy terms for changes in elevation and velocity are negligible and are omitted from the equation. Also, since no mass is entering the control volume during drying, the left side of the equation reduces to the heat that is transferred from the air to the wood. Note that the term for work done by the control volume on the external environment is negligible and is not included in the equation. The right side of the equation therefore reduces to the change of energy within the wood and the energy that is lost from the wood in the form of the mass of water vapor exiting the wood surface multiplied by the enthalpy of the water vapor. The water goes through a phase change from liquid to vapor before exiting. The following expression is true for any instant in time:

\[
\dot{Q}_{c.v.} = \frac{dE_{c.v.}}{dt} + \dot{M}_e (h_e) \tag{2.1}
\]

where,

\[
\dot{Q}_{c.v.} \quad = \text{rate of heat flow into the control volume}
\]

\[
\frac{dE_{c.v.}}{dt} \quad = \text{rate of energy change within the control volume}
\]

\[
\dot{M}_e \quad = \text{rate of water mass flow from the control volume}
\]

\[
h_e \quad = \text{enthalpy of water mass exiting the control volume as a vapor}
\]

This equation can now be integrated between times \( t_1 \) and \( t_2 \) to give:

\[
Q_{c.v.} = (E_{c.v.2} - E_{c.v.1}) + \dot{M}_e (h_e) \tag{2.2}
\]
Fig. 2-1. Control volume for energy and mass flow.
The energy, $E_{c.v.}$, stored within the control volume at any time, $t$, is given by:

$$E_{c.v.} = M \ u_t + m_{\text{wood}} \ W + U$$  \hspace{1cm} (2.3)

Note that capillary energy has been neglected since the sample is assumed to be below the fiber saturation point. The terms are defined as follows:

- $M$ = mass of water within the control volume
- $u_t$ = the thermal internal energy of the water at the given temperature per kilogram of water
- $m_{\text{wood}}$ = the mass of dry wood within the control volume
- $W$ = the integral heat of wetting at the given $m$
- $U$ = the elastic strain energy stored within the wood fibers, which depends on the $m$ profile.

Note that $U$ is equal to zero for the case of no moisture gradient (mass flow rate of zero). The concepts associated with the energy storage terms will be expanded further in the chapter on Discussion and Results.

The equation above (2.2) can now be expanded. There is no summation symbol since it is assumed that mass exits only from the end face of the sample and that the flux is uniform across the exiting area.

$$Q_{c.v.} = (M_2 \ u_{t2} + m_{\text{wood}} \ W_2 + U_2) - (M_1 \ u_{t1} + m_{\text{wood}} \ W_1 + U_1) + M_e \ h_e$$  \hspace{1cm} (2.4)

Since this drying is assumed to be a constant temperature process:
\[ u_{c2} = u_{t1} = u_t \]

\[ Q_{c,v} = (M_2 - M_1) u_t + m_{wood} (W_2 - W_1) + (U_2 - U_1) + M_e h_e \quad (2.5) \]

Note that:
\[ M_2 - M_1 = -M_e \]
and that
\[ h_e - u_t = h_{fg} \]
since \( u_t = h_f \), where
\[ h_f \quad = \text{enthalpy of saturated liquid water,} \]
\[ h_e \quad = \text{enthalpy of water exiting the wood as a saturated vapor, and} \]
\[ h_{fg} \quad = \text{heat of vaporization.} \]

Combining the above gives:

\[ Q_{c,v} = m_{wood} (W_2 - W_1) + (U_2 - U_1) + M_e h_{fg} \quad (2.6) \]

This development assumes that the drying process begins with the sample \( m \) at the fiber saturation point for state 1. For this assumption:
\[ W_1 = 0 \quad (\text{integral heat of wetting}) \]
\[ U_1 = 0 \quad (\text{elastic strain energy}) \]

The following equation for the sample energy balance is then obtained:

\[ Q_{c,v} = m_{wood} W_2 + U_2 + M_e h_{fg} \quad (2.7) \]

This equation states that when wood is dried from the fiber saturation point, the heat energy that flows into the wood is conserved, either as energy stored within the wood or as energy exiting the wood in a different form. The energy can be stored within the wood by two mechanisms; in the hygroscopic energy or in the form of elastic strain.
energy. Energy exits the wood in the form of the heat of vaporization of the mass of water that leaves the wood.

The energy that exits the wood with the mass of vaporized water has a single component. This is $h_{fg}$, the heat of vaporization of the water and has a constant value of $2.4 \times 10^6$ J/Kg water (at 50 C) for all moisture that is evaporated from the wood.

The differential heat of sorption occurs only for the water that is evaporated from the wood when the moisture content is below the fiber saturation point. It varies with moisture content from 0 J/Kg wood at a moisture content above fiber saturation (>30 % m) to a maximum of $1.1 \times 10^6$ J/Kg wood at 0 % m as shown in Figure 2-2 and described by Skaar [10]. An equation for the integral heat of wetting, $W$, in units of J/Kg dry wood, is given as follows:

$$W = e^{11.18 - 12.45m}$$  \hspace{1cm} (2.8)

The other energy storage is that which is done during the development of the shrinkage gradient within the wood. The shrinkage gradient causes the stretching, compression, and bending of wood fibers. It can be shown that most of this elastic energy storage is in the bending of the fibers at the ends of a sample. An equation for this energy storage term (from Eq. A.60) is presented as follows:

$$U = \frac{13}{1620} \frac{L^9 k^2}{EI}$$  \hspace{1cm} (2.9)

where the symbols are as follows:

$L$ = length of the shrinkage gradient at end of sample

$k$ = constant describing parabolic load that bends wood fibers at ends

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Theory and Literature Review

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Fig. 2-2. Differential heat of sorption vs. moisture content.
\[ E = \text{modulus of elasticity} \]
\[ I = \text{area moment of inertia of sample} \]

The total energy that goes into the wood during drying is given as follows:

\[ Q_{c.v.} = m_{\text{wood}} e^{11.18 \cdot 12.45m} + \frac{13}{1620} \frac{L}{E} \frac{K^2}{I} + M_e h_{fg} \]  \hspace{1cm} (2.10)

Most of this energy leaves the wood as the mass of water that is evaporated and its heat of vaporization. The balance of the energy is stored in the wood as hygroscopic energy and the elastic energy storage of the wood fibers bending in response to the differential shrinkage created by the moisture gradient during drying. This energy storage in the wood is given as:

\[ Q_{c.v.} = m_{\text{wood}} e^{11.18 \cdot 12.45m} + \frac{13}{1620} \frac{L}{E} \frac{K^2}{I} \]  \hspace{1cm} (2.11)

It is also shown in Appendix A (see Eq. A.81) that the total maximum elastic energy storage is negligible compared to the energy required to evaporate the water from the wood to dry it (about 1/11,000). In most wood drying analyses this elastic portion of the total energy is neglected. This is justifiable when only considering the total amount of energy required to accomplish drying. This elastic energy is, however, extremely important for wood drying because it creates the mechanical stresses in the material that lead to checks and other drying induced defects. Conventional kiln control techniques measure the enormous energy to evaporate the water (indirectly by measuring moisture loss) when the variable that actually must be controlled is the elastic strain energy. It will also be shown that acoustic emission are a direct indication of excessive elastic strain.
energy in the wood fibers and are therefore a more direct and sensitive variable for feedback to the controller.

**Heat Transfer**

As indicated above, the first consideration when drying wood is the amount of energy that is required and the various components of the energy. A second important consideration in drying wood is the transfer of the energy into the wood through the process of heat transfer. There are two major components to this heat transfer: convection and conduction. A third possible mode of heat transfer, by radiation, is of such a small magnitude as to be negligible for wood drying. The convective heat transfer is from the circulating air to the surface of the wood. The primary variable for the convective transfer of heat in this case is the convective heat-transfer coefficient, $h_c$. This coefficient increases for increased air velocity and is one reason for forcing the air to flow with fans. Convective transfer of heat from the air to the surface of the wood follows Newton's law of cooling [11]:

$$
\dot{q} = h_c A_s (T_\infty - T_s)
$$

(2.12)

where the symbols are as follows:

- $\dot{q}$ = heat transfer rate into the wood
- $h_c$ = convection heat-transfer coefficient
- $A_s$ = surface area of the wood
- $T_s$ = temperature of the wood surface
- $T_\infty$ = temperature of the free stream air

The second important mechanism of energy transfer into the wood is conduction which follows Fourier's law of heat conduction. Conduction heat transfer is important from the surface of the wood to the interior of the wood. For one-dimensional heat transfer:
\[ \dot{q} = -k_c A_c \frac{\partial T}{\partial x} \] (2.13)

where the symbols are as follows:
- \( k_c \) = thermal conductivity
- \( A_c \) = area through which heat conducts
- \( \frac{\partial T}{\partial x} \) = temperature gradient

Wood is a thermal insulator which makes the process of transferring heat into the wood somewhat slow. Low thermal conductivity has the greatest effect when changing the temperature of the wood, as when the wood is first loaded into the kiln and during the drying process when the kiln is changing temperatures. The equations for this have been solved as a function of time for a step change in temperature [12]. In conventional drying technologies the wood spends long periods of time at a constant temperature. The thermal conductivity does effect the drying, however, because as water evaporates within the wood it creates temperature gradients so that the energy content of the wood is not uniform. This has the effect of slowing drying.

**Water Mass Transfer**

Mass transfer must occur to transport water from within the wood to the surface where it can be taken away by the surrounding air. Water mass transfer is made complex by the structure and composition of wood. There are two major categories of mass transfer in wood; one for water above the fiber saturation point and one for water below the fiber saturation point. These are distinctly different because there is liquid water in the cell lumens above the fiber saturation point whereas below the fiber saturation point there is no free water within the wood, it is all hygroscopically bound to the wood material. The following discussion for water mass transfer, which is directed to the
issues concerning hardwoods, is adapted from Siau [12].

The transport of bound water mass below the fiber saturation point is usually defined in terms of Fick's laws of diffusion which state that the flux of moisture movement is proportional to the gradient of moisture concentration under isothermal conditions. The conductivity coefficient is defined as follows:

\[
K_{\text{cond}} = \frac{\text{Flux}}{\text{Gradient}} = \frac{\frac{M_e}{t A_f}}{\frac{\Delta m}{L_g}}
\]  \hspace{1cm} (2.14)

where the terms not defined above are:

- \( K_{\text{cond}} \) = conductivity coefficient for water-vapor diffusion, Kgwater/(% m sec)
- \( M_e \) = mass of water vapor transported, Kg
- \( \Delta m \) = moisture content difference, Kg water per Kg wood expressed in percent

The conductivity coefficient for water vapor has been found to vary with moisture content, temperature, and direction in the wood. It is also affected by some of the same structural considerations as for the flow of liquid water. The moisture diffusion coefficient, which expresses diffusion in m² (wood)/sec is given as follows:

\[
D = \frac{K_{\text{cond}}}{G \rho_{\text{water}}}
\]  \hspace{1cm} (2.15)

where

- \( G \) = specific gravity of wood at \( m \)
\[ \rho_{\text{water}} = \text{density of liquid water} = 1 \text{ Kg/m}^3 \]

When wood is above the fiber saturation point but not completely saturated, there is free water in the cell lumens, and capillary action is a significant force for the movement of water. The small pit openings between cells function as capillary tubes and can pull water from one cell to another and so increase the rate of drying. This tensile force within the cells can be great enough to collapse the cell walls in some circumstances. If a cell lumen fills with air, the tensile force is reduced.

Shrinkage occurs in wood as it dries below the fiber saturation point, and the resulting gradients produce large stresses in the material. Rice [13] has done a detailed study of these shrinkage induced stresses in oak. An interesting part of the study was done on the creep in the material while it is under stress. This creep tends to relax the stress produced by moisture gradients during drying. One portion of the creep is caused by the fact that the wood is changing m while under stress. The resulting creep is called mechnano-sorptive creep which can be up to ten times the magnitude of visco-elastic creep.

Many sophisticated models have been derived to describe mass flow during wood drying. Plumb et al. [14] uses the approach of modeling the wood as a three phase solution. The three phases are the solid cell wall material with its bound water, free liquid water that fills part of the cell lumens, and gas bubbles containing air and water vapor that occupy the remaining lumen space. Theoretical models such as this must integrate the effects of the drying conditions over a long period of time.
Acoustic Emission

An acoustic emission (AE) is a transient release of elastic energy when a material fails under stress. This is a phenomenon that has long been noted during the failure of materials and has attracted research interest for at least 60 years. The audible sounds emitted during the deformation of tin, called tin cry, was studied in 1929 [15]. Kaiser performed the first comprehensive investigation of acoustic emission in 1950, and an important property, the Kaiser effect, bears his name [16]. The Kaiser effect states that when a material is stressed to some state that produces AE and the stress is released, AE will not be detected again in the material (by the same instrumentation) until the stress level has exceeded the previous level that produced AE [17]. Since the time of Kaiser's work, knowledge and applications for AE has grown rapidly for many different materials.

There are many kinds of transducers available for the detection of acoustic emission. Both capacitive and optical transducers have been fabricated to give absolute indications of the surface displacement of the samples for acoustic emission events [16, 17, 18]. The piezoelectric transducer is by far the most common one used for acoustic emission work, and in the majority of investigations the transducer is attached directly to the sample. Piezoelectric-based devices are both low cost and reliable. They are used in basically two ways: resonant and damped. The resonant transducers are the most sensitive while the damped transducers give a flatter response over a range of frequencies. In different regions of its frequency response a piezoelectric transducer may be sensitive to surface displacement, surface velocity, and even surface acceleration [18, 22]. Scruby et al. have found that the sensitivity threshold of piezoelectric transducers can be in the range of $10^{-11}$ mm of surface displacement [18, 23, 24]. Note that the sensitivity threshold of a resistance strain gage is on the
order of $10^{-5}$ mm. Alcoz et al. [25] have recently investigated a new method of detecting AE which uses specially prepared optical fiber as the transducer. A single fiber could be used to detect AE at several locations.

Piezoelectric type transducers are based on special materials that produce an electric charge when deformed mechanically. The most common material used in transducers is a piezoelectric crystal of lead-zirconate-titanate (PZT), usually PZT-5 [18]. Piezoelectric materials are composed of alternating layers of positively and negatively charged material. When there is no external strain, the internal charges are balanced and there is no net charge on the surface. When the material is strained however, the internal layers of charge become unbalanced and a net charge results on the surface. Piezoelectric materials also have the inverse property of generating a strain when excited electrically. A piezoelectric material was utilized both as an excitation transducer and as a passive listening transducer in this project.

A maximum response can be obtained from a piezoelectric transducer by operating it in its resonant mode. The resonant frequency of a given crystal is dependent on its modulus of elasticity ($E$) and on its physical dimensions. A material with a given $E$ can be made to resonate at a given frequency simply by adjusting its geometry. This is desirable for two reasons, both related to sensitivity and signal to noise ratio. First, a piezoelectric crystal gives its maximum signal response at its resonant frequency. If it is desired to monitor some acoustic source, such as acoustic emission from wood, it is optimum to find the frequency of the strongest signal and select a transducer with a resonant frequency corresponding to this frequency. Thus the transducer will give the greatest output at the frequency of interest. Secondly, for monitoring low-level signals, noise is often a problem.
Signals generated by acoustic emission from wood are microvolt level signals. Noise, usually white noise or noise with a broad bandwidth, is always present in any amplifier. When a low level signal is amplified, the noise of the amplifier is amplified with the signal. For acoustic emission from wood the signal is amplified about 100 dB or 100,000 times. For a typical input amplifier noise level of 5 microvolts, the amplifier output noise is 500 millivolts peak to peak.

Fortunately, it is relatively easy to reject frequencies other than those of interest with active electronic filters. The system used in this study had filters for both low frequency and high frequency noise rejection, resulting in a passband from about 45 KHz to about 90 KHz. The intrinsic noise in amplifiers has terms proportional to the bandwidth of the amplifier and also proportional to inverse frequency [26]. Therefore, limiting the amplifier passband helps to increase the sensitivity of the instrumentation for acoustic emission.

A more important reason for frequency selective transducers and electronic filters is the rejection of unwanted signals. These include the sounds of fan motors, pumps, conversation and airflow. Most of these unwanted sounds are at relatively low frequency of less than 20,000 Hz. Note that the resonant frequency of the transducers used in this project is 75,000 Hz. With the transducers and filters used, the problem of interference from unwanted acoustic sources was virtually eliminated.

Harris et al. have proposed that the voltage output from a transducer is an exponentially damped sinusoidal wave with the following form [27]:

\[ V(t) = V_0 e^{-\gamma t} \sin \omega t \]  

\[ (2.16) \]
where
\[ V(t) = \text{output voltage of transducer} \]
\[ V_0 = \text{maximum signal voltage amplitude} \]
\[ \gamma = \text{damping constant (>0)} \]
\[ t = \text{time} \]
\[ \omega = \text{signal angular frequency, } 2\pi f \]
\[ f = \text{linear frequency.} \]
\[ e = \text{base of natural logarithms} \]

If the AE signals are logged by counting the number of times that the waveform crosses a threshold trigger level, then the number of counts measured from an event is given by:

\[
N_c = \left( \frac{\omega}{2\pi\gamma} \right) \ln \frac{V_0}{V_t} \tag{2.17}
\]

\[ N_c = \text{number of counts} \]
\[ V_t = \text{the threshold voltage.} \]

Harris et al. have also proposed that the initial voltage output of the transducer, \(V_0\), is proportional to the square root of the energy released by an AE event as follows:

\[
V_0 \propto \sqrt{E_g} \tag{2.18}
\]

where \(E_g\) is the energy released during microcrack growth. Figure 2-3 illustrates a typical AE event waveform.

Each AE signal is the result of a small burst of energy emitted from the wood as it fractures. This fracture is caused by high tensile stresses resulting from the drying and shrinking gradients. The signal appears as an exponentially damped sinusoidal wave. For wood, each
Fig. 2-3. Acoustic emission event waveform.
emission results in a burst of energy that damps out in about one millisecond. The ring-down count is the number of times that the waveform crosses a pre-set trigger level. Each time the waveform crosses the trigger level it is detected by an electronic comparator and is counted by the computer controller. The waveform for the AE event in Figure 2-3 would result in five counts. A single AE event may result in from one to perhaps a hundred counts depending on the sound damping characteristics of the wood, the magnitude of the emission, and its proximity to the detector. The result is a count rate that indicates the severity of the drying stresses. For example, a reasonable count rate in this study was about 1000 counts per minute. This resulted from moderately severe drying conditions with the trigger level on the comparator set to about twice the maximum amplitude of the noise voltage. It was found that severe drying conditions could result in count rates as high as 100,000 counts per minute for short time periods.

It is difficult to relate the ring down count directly to something physically meaningful since the ring down count is a complex function of the frequency response of the transducer, the damping characteristics of the propagation media, the amplitude of the signal, coupling efficiency, sensitivity of the detector, distance from the source to the detector, and amplifier gain and the threshold voltage [15]. It has been shown that the ring down count is extremely sensitive to the amplifier gain and to the threshold voltage. Much care went into making these parameters as stable as possible for the instrumentation used in this project.

Use of acoustical energy as a nondestructive indicator of physical properties and damage in wood has been investigated for many years. James reported in 1961 [28] that speed of sound and Young's
modulus of Douglas-fir decrease with increasing temperature and moisture content. McDonald in 1978 [29] exploited the difference in sound velocity with sound direction relative to the grain to enable the detection of defects in dry lumber. He used piezoelectric crystals at ultrasonic frequencies as excitation and detection transducers for measuring the speed of sound in samples. Porter [30] in 1964 used acoustic emission to study fracture in wood during mechanical testing and proposed that similar instrumentation techniques could detect defects produced by drying stresses. Progress at that time was limited by the instrumentation that was available. Skaar in 1976 [31] first proposed that AE could be used as a basis for control of the lumber drying process. An overall description of a wood sample with an attached AE transducer, event counter, and feedback control over the drying conditions was given. In 1980 Skaar et al. [32] reported on experimental work that demonstrated the feasibility of using AE to detect drying induced stresses in oak lumber. Similar work was reported by Noguchi et al. in 1980 [33], and also by Becker in 1982 [34]. Experimental work that demonstrated the feasibility of controlling wood drying based on AE detection was reported by Honeycutt et al. in 1982 [35], 1984 [36], and 1985 [37]. This study used a microcomputer to implement closed loop control of drying short lengths of full-sized oak lumber by adjusting environmental conditions based on the rate of AE. Independent experimental work on AE based control of wood drying was reported by Kitayama et al. in 1985 [38] and by Noguchi et al. in 1987 [39].

An additional piece of instrumentation used was an AET 206 Stress Wave Factor (SWF) analyzer. This device makes use of two piezoelectric transducers to gain knowledge of the acoustical properties of the material under investigation. One of the transducers is used as a transmitter and the other as a receiver of acoustic energy.

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The instrument puts short bursts of energy into the wood and measures the sound that is transmitted through. It still uses a pulse counter with a selectable trigger level. Both the amplitude of the injected pulse and the repetition rate of the transmitted pulses can be selected on the instrument. The count rate detected by the receiving transducer gives an indication of the attenuation of sound in the sample material between the two transducers. Michalski [40] used the instrument to indicate sound attenuation in oak. He found a positive correlation between increased checking damage and increased sound attenuation as indicated by the SWF instrument.

Attenuation of sound can vary in a material like wood for a number of reasons. These include checking and splitting damage that can result from severe drying conditions, as well as grain direction, temperature, moisture content, and density. The SWF instrument is excellent for indicating damage as it occurs in a test specimen. Something like this instrument or an equivalent functional element will probably be needed for a commercial controller based on acoustic emission data. The reason for this is that the rate of acoustic emission will be used to indicate the rate at which damage is being done in the wood. If the attenuation of sound varies with the above mentioned parameters and no compensation is done, the same AE data can indicate greatly varying rates of damage. For example, a count rate of 1000 counts per minute under conditions of nominal acoustic attenuation might mean that the rate of damage is acceptable. However if the attenuation of sound in the sample is actually several times that assumed, then the rate of damage may actually be several times greater than that indicated by the measured rate of AE. It is for this reason that monitoring sound attenuation is important when using AE as a feedback parameter to control drying.
Advantage of AE Supplemented Control

It doubtful that a wood drying control scheme will ever be based exclusively on the rate of acoustic emission. It is more probable that AE monitoring will be used as a supplement to other control strategies. Some of the more conventional control methods, if extended, could be quite effective. A possible system would be control based on continuous weight monitoring to assess the moisture content of the wood load, combined with the use of acoustic emission monitoring to help optimize the rate of drying without damaging the wood.

There are a number of possible advantages that can be expected from monitoring AE. First, it should be noted that systems based on the weight of wood are extremely slow to respond. An unacceptable amount of damage can easily be done to the wood long before the change in weight would indicate a problem. The monitoring of acoustic emission can indicate trouble for a moisture loss so small as to be virtually undetectable. The time response of an AE based controller could be extremely fast and updated to a more optimal schedule practically on an hourly basis and respond to severe trouble in a matter of minutes. It should be noted that the basic problem to be avoided is excessive mechanical stress in or between the wood fibers. Monitoring weight to indicate moisture content which in turn must be interpreted as a function of the point in time of the drying schedule to indicate mechanical stress is an indirect and inaccurate process. The measurement of AE is proposed to be used as a direct indicator of the stress state of the wood fibers. A high AE rate indicates a high state of mechanical stress and the drying conditions can be quickly adjusted to correct the situation.

Another advantage of AE monitoring is that since the instrumentation
is relatively inexpensive when amortized over many years of service, many samples in the kiln could be monitored simultaneously. This information could be used in two ways. First, it could indicate environmental variations from point to point within the kiln. In addition, the data could be used on a statistical average basis in order to bring the total load to some average quality level. It will probably always be more economical to allow some small fraction of the material to be damaged and achieve rapid processing than to operate in such a way as to produce absolutely no physical damage to the material. The use of distributed AE monitoring will allow an intelligent and cost optimized tradeoff to be made.

**Control Theory**

The true goal of this project was to investigate the possibility of using the rate of acoustic emission as a control parameter in the drying of red oak lumber. Some general control concepts will be considered in this section. A proposed model of the wood drying process is given in Chapter VI.

In its most basic form, automatic control involves the measurement of some process variables of interest, making a decision based on some pre-determined rules, and taking some corrective action, all under computer control. One of the fundamental concepts in control theory is that of the transfer function, which is given the symbol \( G(s) \). The system transfer function is the ratio of the system output to its input.

An advantage of computer based control is that transducers can be calibrated with an equation to correct for errors in slope, offset, and scaling. In addition, if transducers are non-linear, the equations can fit polynomial calibration curves to linearize them.

The derivation and optimization of feedback control is well
documented in the techniques of classical and modern control theory [41]. The feedback transfer function is called $H(s)$. A diagram showing the concept of both the open loop and closed loop transfer functions is shown in Figure 2-4.

Situations in which the forward transfer function is not known, as was the case for the air heater in the AMINCO and to a much greater extent the transfer function relating the behavior of acoustic emission in response to the drying environment, can still be handled using some form of the Proportional Integral Derivative (PID) algorithm. This technique can be implemented in discrete analog hardware for many systems but it is better suited for the flexibility inherent with digital computer based control. Discussion of the PID algorithm will be aided by reference to Figure 2-5. Fundamental to the use of computers for closed loop control is the sampling interval. Analog controllers work with continuous measurements of the variable to be controlled, whereas computers perform operations in discrete time intervals. The time interval at which a measurement of the output variable and corrections made is called the sampling interval, $t_s$, as shown in Figure 2-5. The PID algorithm, as its name implies, implements feedback compensation through three parts: one proportional to the error, one proportional to the average error over several time intervals, and one proportional to the rate of change in the error. Each term in the control equation has an associated constant of proportionality. Referring to Figure 2-5, the control transfer function is given in the following equation [42]:

$$O_n = G_P e_n + G_I \sum_{t=n \cdot p}^{n} \frac{e_t t_s}{p} + G_D \frac{e_n - e_{n-1}}{t_s} + O_{n-1} \tag{2.19}$$
A. Open Loop Control

B. Closed Loop Control

Fig. 2-4. Control strategies.
Fig. 2-5. Digital control data.
The variables are defined as follows:

\( O_n \) = control equation output at time interval \( t_n \), the most recent.
\( G_p \) = proportional term gain constant
\( e_n \) = error (setpoint value minus measured value of controlled parameter) at time interval \( n \)
\( G_i \) = integral term gain constant
\( e_i \) = error at some time interval \( i \)
\( t_s \) = data sample time interval
\( G_d \) = derivative term gain constant
\( e_{n-1} \) = error at time interval \( n-1 \) (the previous interval)
\( O_{n-1} \) = control equation output at the previous time interval.

Note that the error, \( e_n \), is defined as follows:

\[
e_n = SP - PV \tag{2.20}
\]

where the terms are:

\( SP \) = controller setpoint for the process variable
\( PV \) = process variable

The remaining difficulty in implementing the PID algorithm is in selecting the control gain constants. This can be done empirically, as was done in this project for both the air temperature control and for the control of AE. It is not always necessary to use all three terms in the control law. Some common implementations are for only proportional (P) control, only proportional-derivative (PD), or only proportional-integral (PI). Note that a form of equation 2.19 was used for the control of both air temperature and for closed loop control of drying based on AE rate.
Summary
This chapter has reviewed some basic concepts of energy and mass transport associated with wood drying. It has also discussed the resulting energy storage mechanisms and resulting mechanical stresses in the wood material. Background information has been given to indicate how these stresses result in acoustic emission that can be measured to indicate the rate of damage in the wood. Control theory was also briefly discussed since the end result of monitoring AE is a system to control the drying environment in such a way as to minimize cost in terms of energy, material degrade, and drying time.

Note that it is the rate of energy being input to the wood that is being controlled. The rate of heat energy being input to the wood is not determined by temperature, but by control of RH. This determines how rapidly water can evaporate from the wood and therefore the rate of heat input. The storage of elastic strain energy in the wood fibers is the variable of greatest interest since it can result in excessive checking damage to the wood. This elastic strain energy is directly controlled since the AE resulting from excessive stresses is monitored and used as the primary feedback variable.

The following chapter will describe the equipment and software that is required to implement AE based closed loop control of the drying process. The equipment includes instrumentation to monitor variables such as temperature and relative humidity. It also includes equipment for monitoring AE and the critical variable of sound attenuation. The computer software is also discussed.
III. Experimental Apparatus

In order to make stable and repeatable measurements of AE data, it was necessary to control drying conditions precisely. Preliminary experiments indicated that the rate of AE was highly sensitive to the drying conditions and there was evidence that the rate of AE could respond rapidly to changes in drying environment. Efforts were therefore made to control the drying environment accurately and to maintain conditions constant over time if desired. In order to do this, a small environmental conditioning chamber was used and an industrial microcomputer was interfaced to the chamber to allow for data acquisition and closed loop control over the drying environment. The computer was also interfaced to AE test equipment to make possible the automatic acquisition of data and closed loop control over the drying environment based on the acquired data. An overview of the system electronics and test chamber are given in Figure 3-1.

Equipment Overview

The first part of the study was to develop the instrumentation and computer-based controller for a laboratory sized environmental chamber. A surplus AMINCO (American Instrument Company) environmental chamber was made available for the study. It was rebuilt to take advantage of modern control hardware and techniques. Bi-metallic temperature sensing elements were replaced with solid state probes from Analog Devices. Unreliable mechanical relays and timing motors were replaced with solid state relays and microcomputer control. The old refrigeration control was replaced with a hot-gas-bypass system to give good control of the water bath temperature and thus relative humidity. A small industrial microcomputer was interfaced to the environmental chamber to allow periodic logging of data as well as keyboard input of control setpoints.
Fig. 3-1. System overview.
for the drying conditions. With the computer programmed to provide proportional integral derivative (PID) control, the drying conditions could be held constant to within about 0.1 C dry-bulb and 0.5% relative humidity. A second PID loop was eventually implemented to vary the environmental conditions to maintain a constant rate of AE from oak samples.

The computer used in this study to log data and also to control the conditioning chamber was the Rockwell AIM-65. This was a low cost microcomputer designed expressly for dedicated industrial computer applications. The single board computer included a keyboard, 20 column LED alphanumeric display, on-board 20 column printer, as well as ICs for interfacing to off-board devices. One of these ICs was a R6522 versatile interface adapter (VIA) chip. The VIA contained two 8-bit programmable interface ports and a 16 bit internal counter. The counter was used to log AE counts while the interface ports were used to control external equipment and input data. Several additional VIA's were used to complete the required computer interfacing.

Instrumentation for the system consisted of transducers for the measurement of test chamber environmental conditions along with the resulting acoustic emissions from the test sample, custom electronics to interface these transducers to the computer, and some custom electronic hardware to allow the computer to control the environmental conditions. Environmental measurements were based on commercially available temperature transducers which were arranged to allow measurement and control of both dry and wet-bulb temperatures for relative humidity calculation and control. Commercial acoustic emissions transducers were used to indicate activity from two samples simultaneously as well as the sound attenuation characteristics of one sample under observation. The

Chapter III

Experimental Apparatus
electronics that were designed to interface these transducers to the microcomputer will be discussed in Appendix B. In addition, a small commercial scale was used in the chamber to give an indication of the moisture content of the wood samples. This effort had moderate success because the scale sometimes operated erratically with the high temperature and high relative humidity used in some of the experiments.

**Acoustic Emission Measurement**

Acoustic emission instrumentation included a considerable amount of equipment on loan from Acoustic Emission Technology Corp. of Sacramento, California. This equipment consisted of several transducers with constant force spring clamps, preamplifiers with bandpass filters, and an AET 206AU Stress Wave Factor analyzer. Several piezoelectric resonant transducers were tried; the AC30L, AC75L, and the AC175L. The AC75L transducer, which has a resonant frequency of 75 KHz as the part number implies, gave the most sensitive response to the acoustic emission, and was therefore the one selected for monitoring AE during the remainder of the work. The AC75L has a peak resonant sensitivity of -80dB referenced to 10V/Pa (1V/μ bar), and is rated for a service temperature range of -253 C to 163 C [43]. The AET transducers had no difficulty withstanding any of the high temperature, high RH environments they were exposed to during the testing of this project. Each transducer is resonant at a different frequency and has a matching filter pack for the pre-amplifier. The AC75L transducer has an accompanying filter pack with a passband of 45 KHz to 90 KHz. Two transducers were monitored continuously by the computer. The threshold level for counting the AE was set high enough to avoid all electronic noise and yet low enough to give sensitive indications of damage occurring in the test sample boards.

*Chapter III Experimental Apparatus*
The transducers were used in basically two configurations. One configuration consisted of a single transducer attached near the end of a sample board and was used only for the detection of AE. The second configuration used two transducers which were attached near an end but on opposite sides of a sample board as shown in Figure 3-2. This second configuration could also be used in conjunction with the Stress Wave Factor (SWF) analyzer. When used in this mode, one of the two transducers provided pulses of sound into the wood and the second transducer measured the amount of sound transmitted through the wood after being attenuated. In this way it was possible to evaluate the change in sound attenuation within the wood during the course of drying. The SWF measurements were made manually but fortunately the sound attenuation characteristics of the wood did not change rapidly with time and daily readings were sufficient. The SWF was used to indicate how the attenuation of sound changes because of all the interacting factors of temperature, moisture content, and accumulated damage.

As illustrated in Fig. 3-2, the transducers were directly coupled to the wood surface using constant force spring clamps with about 53 N (12 pounds of force). High vacuum grease was spread between the transducers and the wood surface to improve the acoustical coupling. Two channels of AE events were logged. Channel 1 had a Pre-Amp gain of 40 dB which was followed by a gain of 60 dB in the AET 206 SWF instrument. Channel 2 had a Pre-Amp with a gain of 60 dB. An additional gain of 40 dB was provided in the comparator circuitry, as will be explained. Therefore, each of the two channels had a total gain of 100 dB, which was the gain necessary to make the microvolt level signals of the AE events convenient to detect with an electronic comparator.
Fig. 3-2. Sample with transducers.
Temperature and Humidity Measurement
The primary indicators of drying conditions were the dry-bulb and wet-bulb temperatures. Both measurements used solid state temperature transducers from Analog Devices: the AC 2626 temperature probe which was calibrated to an accuracy of $\pm 0.1$ C. This transducer contains an integrated circuit which outputs a current that is linearly proportional to Kelvin temperature. The advantage of this particular transducer is that it gives a high level signal that does not require amplification. In addition, since it is a temperature to current transducer, its calibration is unaffected by the length of wire between it and measuring devices. This probe is also protected by a stainless steel sheath which protects the transducer from the harsh environment of the drying chamber.

Three of these temperature transducers were used, one each to measure dry-bulb temperature and wet-bulb temperature in the wood drying chamber, and one to measure the temperature of the water bath for the humidity control of the drying chamber. The wet-bulb temperature was indicated by the conventional method of covering a temperature probe with a wetted wick and blowing air across the transducer with a small fan. This is the method currently used in commercial kilns to indicate relative humidity. The lower the humidity of the air, the more rapidly water evaporates from the wick and the lower the temperature of the transducer. The three temperature transducers and the scale were interfaced to the computer via a 12 bit A/D converter and multiplexer.

Control Software
Software for logging data and controlling the kiln was written in BASIC since this language was available on the computer that was used in the study. Figure 3-3 gives the program flowchart. The
Fig. 3-3. System software flowchart.
program listing is given in Appendix C. Depending on the experiment being done, the software could be operated in any of several configurations. First, it could be set to hold conditions at preset conditions until a change was manually input to the keyboard. This was useful for the open loop experiments to study AE response to both large and small step changes in drying conditions to determine the dynamic response of the system. A second software configuration allowed closed loop control of the drying conditions to maintain a preset AE count rate. One method used was to hold the chamber water bath temperature constant and adjust RH by varying dry-bulb temperature to maintain a preset AE count rate. This was the one used for the closed loop data presented in the following Chapter and illustrated in Figure 4-4. A disadvantage of this approach was that changes in temperature also changed the sample’s sound attenuation. However, this did not prevent the demonstration of closed loop control of the drying conditions based on AE which was one of the objectives of the project. A better approach, but one not used in these experiments, would be to hold dry-bulb temperature constant and adjust RH by changing the water bath temperature to maintain a constant AE count rate. Compensating for changes in sound attenuation would eliminate the problem but would also require more data than was available at the time of the experimental work.

The program was initiated by manually inputting the control setpoints for initial environmental conditions, and the desired AE setpoint for closed loop control experiments. The program then operated in a simple series of loops. On each loop through the program, which required several seconds, the temperature transducers were read, RH was calculated and the data displayed. Based on this data, power to the water bath and dry-bulb heaters was adjusted to maintain the environmental setpoint conditions. Note that control for the water
bath was either heat full on or cooling full on, and power to the air
heaters was proportional to the error from the setpoint with the power
level determined by a PID algorithm. At the end of each ten minute
period the average AE count rate data was displayed and printed.

Additional software was implemented in the case of closed loop control
of the AE count rate. At the end of each ten minute period, the AE
data was used in a PD or PID algorithm to update the environmental
setpoints. In this way, the environmental conditions were varied to
maintain a constant count rate. After updating the environmental
setpoint, the main program loop was repeated.
IV. Experimental Procedure and Results

Work on this project began with hand made equipment that was used to investigate the feasibility of detecting acoustic emissions produced by drying stresses. It progressed to sophisticated commercial AE equipment and a demonstration of closed loop control of the drying process based on the rate of acoustic emissions. The work did not achieve commercial viability to replace or augment conventional drying controls. The primary focus was investigation of fundamental issues associated with the technology. This included studies of system dynamics which is the foundation for the development of a successful control system.

This chapter details a series of experiments done to investigate AE based control of wood drying. The experiments were done to fulfill several objectives in support of the hypothesis that AE data can be used as the primary control variable for drying hardwoods. The literature reviewed in Chapter II concerning AE research with many materials, along with observations during the presently described experimental work, support the conclusion that AE indicate fracture damage done in a material. All experiments indicate that the instrumentation is sufficiently sensitive to monitor AE from wood in environments approximating those in commercial kilns. In addition, equipment described in the preceding chapter was used to demonstrate closed loop control of the drying process based on AE. Following a description of this work, experiments are described for investigating a low cost method of measuring the important variable of sound attenuation in the samples. This problem is crucial for attaining a commercial controller based on AE. Finally, experiments are described which investigated the dynamic response of AE from wood resulting from controlled step changes in environmental
conditions. These experiments are important for attaining a stable control loop. In short, all the experiments described in this chapter are in support of the objectives supporting the hypothesis that AE can function as the primary feedback variable for the control of drying hardwoods. The experiments represent a connected and logical progression of increasingly sophisticated work toward reaching the goal of an AE based controller.

The earliest experiments used small samples of pine wood that had been oven dried, attached to an AE transducer, and then one end dipped into a beaker of water. As the water wicked rapidly into one end of the sample, the swelling introduced stress gradients. Since this produced detectable AE (as well as audible sounds), the next step was to monitor AE in short lengths of 50 mm (2 in.) by 100 mm (4 in.) oak lumber that had been recently cut and were exposed to room drying conditions. Since this experiment also produced detectable AE, the next step was to determine if increasing the humidity of an enclosed space surrounding a sample would reduce the rate of AE. These early experiments led to the development of the hypothesis that if AE could be used to monitor the severity of drying conditions, then that information could be used to control the drying process. A period of experimentation and equipment development followed which led to the experimental apparatus described in the previous chapter. This equipment made it possible to study drying induced AE in increasingly well controlled environments.

Many subsequent experiments were done with lumber full sized in cross section, but short in length. The progression of experiments first exposed wood to crudely controlled large step changes in environmental conditions to study the effect on these bigger samples. Later experiments added precision to the control of environmental
conditions. This increased precision was first used to study the response to large step changes in drying conditions but was later used to study the feasibility of closed loop control of the drying environment based on the rate of acoustic emissions. Intermediate experiments were performed using an instrument capable of indicating sound attenuation properties of the wood, as well as some experiments using an alternate method of acquiring this information. Some work was also done to study alternate algorithms for control. Finally, to gain a deeper understanding of the dynamic response of acoustic emission rates, the AE from a wood sample were monitored when exposed to small step changes in drying conditions.

Before proceeding, a comment should be made about the absolute magnitudes of the AE data. Over the course of the investigation several transducers, amplifiers, and comparator trigger levels were used. The level of sensitivity for detection of AE was never correlated to an absolute standard since the equipment for calibration was not available. This lack of calibration was not a great problem since the type of experiments performed were not too dependent on a knowledge of the absolute calibration. Most experiments were designed to measure system time response. Therefore, at least at the stage of progress achieved during this study the lack of an absolute calibration was not a serious handicap. When a full commercial controller is developed, of course, the calibration will become more essential. A commercial controller will require a specific count rate for the control setpoint, and associated with this setpoint will be an expected rate of damage to the wood. The following is a description of some of the experiments, beginning with the procedure for sample preparation.

**Sample Preparation**

Since many of the early experiments were done quite quickly to learn as much as possible in a short period of time, the preparation of
samples began somewhat crudely but evolved into a more sophisticated procedure. The following is a description of the final technique of sample preparation and one that is believed to correct many of the deficiencies experienced in early experiments.

The sample size was chosen to fit several constraints. First, the samples had to be small enough to fit in the environmental chamber. Second, the sample size had to be large enough to give data that would correspond to wood commonly dried in commercial full size kilns. The drying stress in wood is closely related to the cross section size of the boards and less to length of the board if the length is above some minimum. Since the drying problems increase with the physical dimensions of the sample, the boards were chosen to be approximately 50 mm by 100 mm (2 inches by 4 inches) in cross section. The length was chosen to be about 300 mm (12 inches) to enable the sample to fit inside the chamber. For these experiments, most of the drying was from the ends of the samples since the samples were so short. For full length lumber, most of the drying is from the face of the wood. However, the principles are the same, and one experiment did indicate that full length samples behave in basically the same way as the short ones. Experiments were also performed which indicated that the AE events from one end of a 300 mm sample board could not be detected at the other end of the sample; the attenuation of sound was simply too great.

The goal of this method of sample preparation was to control the environment that the samples encountered between the log and the environmental chamber. This ensured that the samples would be in a known state. Additional considerations were to provide uniform sample dimensions, smooth surfaces for coupling the transducers to the samples as well as providing smooth surfaces so that check
damage would be easily visible. The following sample preparation was used for all experiments that used the AET equipment and is recommended for future work.

1. A red oak log from a tree that had been recently cut was rough sawn into 55 mm by 105 mm cross section boards. These boards were then cut to 740 mm lengths, double wrapped in plastic bags to reduce moisture loss and stored in a refrigerated room.

2. When ready to run an experiment, boards were removed from refrigerated storage and planed an equal depth on all sides to a final cross section of 100 mm by 50 mm. This provided smooth surfaces as well as removing the outer layer of material that might have dried somewhat. The boards were then cut into two pieces roughly 370 mm long. The ends of the resulting two boards that were from the center of the original 740 mm board were the ones on which the AE transducers were mounted. This was to avoid any end areas with moisture gradients and to provide matched samples for the transducers. About 13 mm was then removed from the end opposite the transducer end and discarded. Finally, 25 mm strips were then cut from each of the four ends to measure the initial moisture content of the samples. The final length of the AE samples was 300 mm.

3. The conditioning chamber was set for a dew-point temperature of 34 C and a dry-bulb of about 35 C to give a RH of about 92%. The samples were loaded into the chamber and mounted on foam rubber supports for vibration damping.

4. The transducers were mounted on the samples midway across the width and about 13 mm from the end as was shown in Fig. 3.2.

5. The conditioning chamber door was opened as seldom and as briefly as possible after the drying run was begun.
Early Dynamic Studies

In order to effect a stable control loop, it was necessary to acquire some knowledge of the system time response. Indications of the time response was acquired in some quick but illustrative experiments. The data for one of these runs is given in Figure 4-1. In this experiment, a green sample of red oak wood measuring 30 mm by 100 mm by 300 mm with an AE transducer attached was placed into a small plastic lined enclosure for several days. At this point the average AE count rate was about 30 CPM and the cover of the enclosure was removed which allowed the RH of the air surrounding the sample to drop. The count rate of AE then began to increase and within 90 minutes had reached a maximum of 10,000 CPM. About 1/2 hour later the enclosure was again covered with plastic and the count rate decreased to about 500 CPM within 2 hours. The enclosure was again opened and the count rate again rose but only to a peak of about 6000 CPM after 1.5 hours. When the enclosure was again wrapped, the count rate decreased to about 1000 CPM after 2 hours. Note that for the second exposure the sample did not reach as high a count rate. The sample was left wrapped overnight and was then unwrapped and exposed to low velocity forced air from a fan. This time the count rate reached a higher peak in less time. The count rate changed from about 600 CPM to a peak of about 14,000 CPM within 20 minutes.

This experiment gave considerable information even though the conditions were not well known or controlled. It demonstrated that changes in relative humidity could control AE count rate. It showed that the time constant for these emissions was on the order of one hour and that forced convection, which increased the severity of the environmental change, speeded the response. This experiment and several similar ones led to the conclusion that it might be possible to use AE information to control the drying of wood. The positive results

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Experimental Procedure and Results

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led to the development of more sophisticated environmental controls and instrumentation to make it possible to perform more detailed experiments.

**Large-Step Humidity Experiment**

Figure 4-2 gives a plot of the results of an experiment that was similar to the one described above, except that the environment was closely monitored and controlled. It gives the response of a 300 mm length of a green 50 mm by 100 mm oak sample to a large step change in humidity. Note that reducing RH increased the AE count rate and vice versa. Several things should be noted about these data. First is the "dead time" that elapsed from the time at which RH began to decrease to the time at which the rate of AE began to increase. Dead time is common in control systems and is sometimes called "transport delay". In this case it is probably caused by the requirement that time is required for water transport to shrink the wood somewhat to generate the mechanical stresses that result in acoustic emissions. Time is required for this shrinkage to exceed the threshold for emissions to occur. It can be seen that this dead time is about 45 minutes. Also note that the peak count rate was about 6000 CPM and that the rise time to this count rate was about 2 hours. The count rate began to decrease somewhat by itself after reaching the peak, but when the RH was increased the count rate rapidly returned to a low level. This response to large step changes in environmental conditions was found to be quite rapid when compared to subsequent experiments with exposed samples to small step changes in drying conditions.

This sample was maintained at the high RH (90-95%) overnight and then the experiment was repeated 5 times at one day intervals. Table 4-1 summarizes the data for these experiments. Note that the dead
Fig. 4-2. Graph of Sample 1-1 data.
Table 4-1. Variation of dead time and peak AE rate for five successive daily cycles.

<table>
<thead>
<tr>
<th>Cycle #</th>
<th>Dead Time</th>
<th>Max Count Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5 Hours</td>
<td>5500 CPM</td>
</tr>
<tr>
<td>2</td>
<td>1.0 Hours</td>
<td>4500 CPM</td>
</tr>
<tr>
<td>3</td>
<td>1.5 Hours</td>
<td>2800 CPM</td>
</tr>
<tr>
<td>4</td>
<td>1.8 Hours</td>
<td>2300 CPM</td>
</tr>
<tr>
<td>5</td>
<td>1.8 Hours</td>
<td>2100 CPM</td>
</tr>
</tbody>
</table>
time increased and the peak count rate decreased with each succeeding cycle. The time lag recorded as dead time is an example of a combination of transport delay and the Kaiser effect discussed in the Acoustic Emissions section of Chapter II; each cycle required more water transport time to produce the shrinkage necessary to exceed the level of stress of the previous cycle and result in AE. For the fifth run the dead time had increased to about 2 hours and the peak count rate decreased to about 2000 CPM. These experiments were important because they demonstrated the strong relationship between drying stresses and AE rate; decreasing the RH resulted in an increased AE rate and increasing the RH decreased the AE rate. The experiments also gave some early information on the time response characteristics of the samples, which was useful for setting up a controller for the closed loop experiments that followed. Information on the change in dead time and sensitivity as the drying of the sample progresses is especially noteworthy since it indicates that the dynamics of the AE response changes as a function of the sample m and its drying history.

**First Closed Loop Drying Experiment**

After a few short trial runs to empirically determine a workable controller gain, the chamber was loaded with a sample of red oak that had been instrumented with prototype AE equipment. The environment of the chamber was held at a constant dew-point temperature, and the dry-bulb temperature was varied to control the rate of AE. In this first run the AE sample was removed periodically to monitor its moisture content. The goal of the experiment was to maintain a constant rate of AE at a predetermined setpoint level chosen arbitrarily to be 1000 CPM. Based on previous experience, this rate of AE was expected to result in a low rate of end checking damage in the samples. Figure 4-3 shows curves of the AE count rate
and relative humidity plotted against drying time. The run progressed smoothly for about four days. During this time the AE count rate was held relatively constant at near 1000 CPM by the computer, which modified the drying conditions at 10 minute intervals. The general trend was for a gradual reduction in the RH. After about four days, however, something changed so that the controller gain was no longer suitable. With this gain the control loop was only marginally stable. After four days of drying, both the rate of AE and the environmental conditions became unstable and the system oscillated between severe and mild drying conditions as shown in Figure 4-3.

There were two probable reasons for this instability. First, the AE sample was physically removed from the environmental chamber for several minutes so that it could be weighed for determinations of \( m \). Since the air outside the chamber represented a relatively severe drying environment the count rate rose to a high level and maintained a high level (3000 CPM) for about an hour after the sample was returned to the chamber. The computer monitored the emissions and called for large increases in the drying humidity thus overcompensating. The second reason for instability was that the controller gain was set too high. Therefore the environmental chamber could not change conditions fast enough to keep up with the change in humidity setpoint that was called for by the computer. This phase lag contributed to instability since the computer was dictating a large and rapid change in environment before the chamber or the wood’s AE rate could respond. For example, on the fourth day of the drying run before the sample was removed from the chamber to be weighed, the dry-bulb temperature was about 44 C and the RH was in the range of 55%. After the sample was returned to the chamber and the count rate rose to its maximum of about 3000 CPM in the first peak, the computer decreased the dry-bulb set point from 44 C to

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29 C which increased the RH to 84%. By the time the AE count rate had returned to the setpoint of 1000 CPM two hours later, the dry-bulb setpoint was only 20 C and the measured dry-bulb temperature was 30 C. The chamber could not reduce the dry-bulb temperature any lower because that was the temperature of the water bath used for wet-bulb temperature control. The RH at this point had increased to about 90%. Three hours later when the dry-bulb setpoint was back up to the measured dry-bulb temperature of 30 C the count rate was at 300 CPM and the RH was still at 90%. Three hours later the drying conditions were back to the setting before the sample was removed for weighing; a dry-bulb of about 44 C and a RH of about 50% but the count rate was down to 60 CPM. Six hours later when the count rate was back at the setpoint of 1000 CPM the dry-bulb temperature was up to 60 C and the RH down to 32%. Note that throughout this excursion the actual RH was lagging greatly behind what it should have been to control the AE count rate effectively. It may also be that the continually increasing transport delay time within the wood contributed to the overall phase lag. This may be the reason why several days of drying passed before the system became unstable.

**Second Closed Loop Drying Experiment**

A followup experiment used a reduced setting for the controller gain and produced more desirable results. The plot shown in Figure 4-4 gives the results for this experiment. Note that the rate of AE was relatively constant throughout. The relative humidity was reduced smoothly to achieve this result.

Two green matched samples of red oak were loaded into the chamber. One was instrumented for AE and the other was removed periodically for m measurements. This greatly reduced the exposure of the AE sample to the uncontrolled environment and had a less severe impact on the controller. The samples were red oak with dimensions of 270
Figure 4-4. AE based control of drying process. (Sample 3)
mm length by 43 mm radial by 87 mm tangential. The water bath temperature (dew-point) of the AMINCO was kept at 35 C and the dry-bulb temperature was varied to control the humidity, and hence the severity of the drying environment. The controller gain, G, was reduced from the previous experiment by a factor of ten to 0.0001 C/CPM; a value empirically chosen based on previous experience. This means that the dry-bulb temperature was increased by 0.0001 C for a count rate error of 1 CPM below the setpoint. The count rate was monitored continuously and the controller modified the dry-bulb temperature setpoint every 10 minutes. For example, if the setpoint was 1000 CPM and the actual reading was 900 CPM, thus giving an error of 100 CPM, then the dry-bulb temperature was increased by 0.01 C for that 10 minute period. There was also a derivative term in the control equation which modified the change in dry-bulb set point based on the rate of change in the acoustic emissions data from the previous ten minute time period to the present. The gain for this term was a dry-bulb decrease of 0.0001 degree C for an increase in count rate of 1 between the last two readings. The effect of this term was to increase the rate of dry-bulb set point changes if the rate of change in AE was great. The control equation is given as follows:

\[ T_{DBn} = G_P e_n + G_I \sum_{i=n-p}^{n} \frac{e_i t_s}{p} + G_D \frac{e_n - e_{n-1}}{t_s} + T_{DBn-1} \]  

Eq. 4.1

Where the variables are defined as follows:

- \( T_{DBn} \) the new dry-bulb set point at time \( n \)
- \( T_{DBn-1} \) the old dry-bulb set point at time interval \( n-1 \)
- \( G \) the coefficients specifying the controller gain
- \( e_n \) count rate error, count rate setpoint minus measured count rate
Note that this is the master PID control loop that sets the new dry-bulb set point to determine the RH that will maintain the AE count rate at the setpoint. There is an inner control loop to maintain the dry-bulb temperature at the setpoint determined by Equation 4.1. For data presented in Figure 4-3 and 4-4 only the proportional and derivative terms in the equation were used. During the first 8 hours of the run the relative humidity was reduced rapidly (see Figure 4-4) since it started at about 86% RH; a high-humidity environment that resulted in a low count rate. As the count rate increased, the rate of RH decrease was slowed by the controller. The rate of RH reduction was fairly constant until about 5 1/2 days into the run when the AE decreased rapidly and the controller reduced the RH rapidly to compensate. When it was observed that the increasingly severe drying environment was not sufficiently dry to return the count rate to the setpoint, the fasteners that attached the AE transducer to the sample were tightened. This increased the count rate for a short time by improving the acoustical coupling between the sample and the transducer. However, it soon became apparent that the emissions had slowed simply because of reduced stresses as the sample approached a dry state, and the run was therefore terminated. It is possible, however that the measured AE rate decreased because at the high dry-bulb temperature in the chamber (about 65 C) that the sound attenuation properties of the wood was high.

Note also in Figure 4-4 the two peaks in count rate (each about 1700 CPM) that occurred shortly after one day and at two days into the run. These were instances in which the chamber door was opened to remove samples for moisture content measurements. The peak count rate during the period in which the door was opened was actually much higher that 1700 CPM. However, this high rate was only for a short time whereas the data plotted are for one hour averages. Note especially how the controller responded to the first peak by increasing
the RH and how this resulted in a dip in the AE for a few hours after
the door was opened until the controller could stabilize the situation.
When the door was opened for subsequent measurements at 3 days
and later, the sample was no longer so sensitive to brief changes in
the drying environment and peaks in the count rate were not
observed. The probable reason for this is that the outer surfaces of
the sample had dried somewhat and the brief change in drying
conditions were not enough to disrupt the profile of $m$ within the
sample.

Figure 4-5 shows how the average $m$ of the matched sample
decreased from the initial value of 69% to the final value of about
20%. The dry-bulb temperature changed during the run from the
initial 35 C to a final value of 65 C, the highest that the system could
achieve. The first visible end check was observed at 2 1/2 days.
About 2,000,000 counts of AE had been logged at this point. After the
run was completed the samples were weighed and 5 strips each 25
mm long were cut from the end to measure the $m$ profile. It was
found that $m$ varied from about 7% at the end to 27% in the interior.
The data are plotted in Figure 4-6.

Note that the actual count rate observed was almost always below the
setpoint of 1000 CPM. The reason for this is that the control routine
was a PD controller and not a PID routine. When the error was small
the gain was not sufficient to allow the AE count to reach the setpoint.

**PI Control**
The preceding experiment used a Proportion-Derivative (PD) controller
and as a result the count rate was consistently below the setpoint.
This was not a real problem since the setpoint was chosen arbitrarily,
and a small but consistent error is nonconsequential. In order to

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Fig. 4-5. Sample 3 moisture content change.
Fig. 4-6. Moisture content profile of Sample 3.

Sample average moisture content = 19.7%
Data is for 25 mm strips
Data taken at end of drying run
prove that it could be done however, the control law was changed to Proportional-Integral (PI). In this case the controller considers the average count rate over many time periods instead of just the present time period. This allows the controller to make adjustments to the environment based on an average error and it can then reach the setpoint. With only PI control, however, the system tends to significantly overshoot the setpoint. Addition of the derivative term in the control equation, which makes it a PID controller, solves the overshoot problem.

**Logarithmic Control**
Most of the closed-loop control experiments were done using a linear control law. In effect, the correction to the environmental conditions were done linearly related to the error in AE reading. Note however that the AE count rate is a non-linear function of the rate of drying. No counts at all are recorded until the rate of drying gets up to some threshold value to produce the required moisture and shrinkage gradient to result in AE. In an effort to increase controller stability, an experiment was done in which the control law was based on the logarithm of the count rate. Large transients in the count rate, as occurred when the drying chamber door was opened, then do not result in an unduly large change in the environmental conditions while small errors in the count rate still result in a large enough change in the environment to be effective. Implementation of this concept is recommended but additional work must be done to ensure optimum controller gain.

**Stress Wave Factor Experiments**
Measurement of the sound attenuation properties of wood samples is essential to effective utilization of AE information. Sound attenuation in a given wood specimen and at a particular grain orientation is
dependent on accumulated damage, moisture content, and temperature. The AET 206AU Stress Wave Factor (SWF) instrument was used in a number of experiments to investigate its ability to monitor changes in sound attenuation in wood samples during drying. The process of drying wood changes all three of the variables that affect sound attenuation. Since drying without a significant temperature change is easy to accomplish in the laboratory, many experiments were done at constant temperature. However, some additional experiments were performed using changes in temperature specifically designed to investigate alternate ways of interpreting the SWF data that could be obtained from the AET 206AU, as well as to investigate an alternate method that was found to give somewhat different results.

Recall that the SWF measurements are accomplished by using two piezoelectric transducers mounted on opposite sides of a sample one used as a transmitter and the other as a receiver. The transmitting transducer is pulsed with energy and the receiving transducer monitors the waveform of the sound energy that is propagated through the sample. As with conventional measurements of AE, the SWF instrument utilizes an electronic comparator with a reference trigger level and counts all peaks in the received waveform that crosses the trigger level. The transmitter pulses the sample repeatedly and displays a running count average to indicate SWF. The number is dependent not only on the sound attenuation properties of the sample but also on the particular value of the trigger setpoint in the receiver. This is somewhat arbitrary and is controlled by the instrument operator. The instrument is actually intended to be used to search for damaged areas in a material and does this by displaying changes in the SWF reading through different areas of a material. For work with the wood samples, both transducers were
kept at fixed locations and the display was used to detect changes in sound attenuation as a function of time. As noted above, these experiments were carried out to detect SWF changes caused by temperature changes in the wood.

Data presented in Table 4-2 summarizes the results of the measured changes in SWF for different sample temperatures. The SWF decreased from 2700 to 1300 for an increase in temperature from 40 C to 60 C. As an additional step, measurements of SWF for different amplifier gain setting were made with the trigger level and all other instrument settings held constant. These data are plotted in Figure 4-7 and indicate that the logarithm of SWF is a linear function of the logarithm of amplifier gain reduction. The slopes of these lines are also related to the sound attenuation properties of the wood samples. Notice that, as the temperature is increased from 40 C to 60 C, the slopes of the lines become increasingly negative. These data as well as the same data presented normalized to the maximum reading are also given in Table 4-2, and are plotted in Figure 4-8. It is quite possible that the slope of the line for SWF with trigger level is a more sensitive indicator of sound attenuation than is the more simple SWF measurement. Figure 4-8 also indicates that the slope measurement may be a more sensitive indicator. The slope measurement has the added advantage that it is not sensitive to the particular instrument settings. For example, an increase in the energy that is injected into the sample by the pulsing transducer will only influence the absolute magnitudes of the lines in Figure 4-7 but not the slopes of the lines. This will also be true for changes in amplifier gain settings and specific trigger level settings.

The SWF instrument was a sensitive indicator of changes in sound attenuation in the wood samples. This measurement is very important since the information would be necessary in a commercial
### Table 4-2. Variation of Stress Wave Factor with temperature.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>SWF</th>
<th>Normalized SWF</th>
<th>Slopes</th>
<th>Normalized Slopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 C</td>
<td>2700</td>
<td>1.00</td>
<td>-0.016</td>
<td>-0.30</td>
</tr>
<tr>
<td>50 C</td>
<td>2000</td>
<td>0.74</td>
<td>-0.028</td>
<td>-0.53</td>
</tr>
<tr>
<td>60 C</td>
<td>1300</td>
<td>0.48</td>
<td>-0.053</td>
<td>-1.00</td>
</tr>
</tbody>
</table>
Fig. 4-7. Log (Stress Wave Factor) vs. amplifier gain reduction.

Notes: No visible checks at any time.
Pulser = AC175L
Detector = AC75L

Temp = 40°C
\[ y = 3.46 - 0.016x \]
\[ R^2 = 0.980 \]

Temp = 50°C
\[ y = 3.38 - 0.028x \]
\[ R^2 = 0.998 \]

Temp = 60°C
\[ y = 3.31 - 0.053x \]
\[ R^2 = 0.974 \]
Fig. 4-8. Normalized plots of SWF and slopes.
controller to compensate the AE count rate measurement for changes in sound attenuation. However, the necessity of making the measurement for each transducer might make a commercial controller based on AE prohibitively expensive. In an effort to develop a more cost effective method of measuring sound attenuation, an unconventional approach was also tried, and the results are given in Figure 4-9. The concept used was to make slope measurements similar to the ones done with the SWF instrument and presented above, but instead of using a transducer to pulse energy into the wood, use the acoustic emissions themselves as the driving energy source for the measurement. This method has the advantage that the sound attenuation of the sample can be measured using only a single transducer, the same one used to monitor AE, thus saving the cost of both the transmitter and second transducer as well as perhaps giving a more accurate indication of sound attenuation. The data given in Figure 4-9 was obtained by monitoring a sample that was held at a constant drying environment and also during a period of relatively constant count rate. Each data point represents a 10 minute average of the count rate with a different amplifier gain setting. Therefore each curve required about one hour to acquire the data. This was done for each curve at 35 C and at 45 C. For a production system the data for the multiple data points used to determine the slope of the line could be obtained by using multiple comparators and counters. Note that the method does detect a change in slope for the two temperature conditions. The difference in the slope for the two temperature settings are not large, but it is probable that the sample may have dried somewhat before that measurement was done at the higher temperature and therefore that data are not exactly comparable with those at the lower temperature.

One difference is noted between the slopes obtained using the pulser
Fig. 4-9. Count rate vs. amplifier gain reduction.

Temp = 45 C
y = 3.82 - 0.0924x
R^2 = 0.996

Temp ≈ 35 C
y = 3.55 - 0.0852x
R^2 = 0.996
of the SWF instrument in Figure 4-7 and that obtained using AE as the driver in Figure 4-9. The main difference is that the slope of the lines obtained using the AE driver is much steeper. The slope for the AE driven data is about -0.09 as compared to -0.02 for the pulsar driven data. There are two probable reasons for this difference. The first is that the pulser used by the AET 206AU is a high "Q" piezoelectric device. Since it is high Q, it will continue to oscillate for a relatively long time and therefore continue to drive sound energy into the sample and make it appear that the ringing of the sound pulse is not being damped out as quickly. It is probable that the transducer is causing an erroneous slope to be derived from the data. The AE method uses the natural ringing of the material to generate the information and therefore may be a more accurate indicator for the slope of the line. In other words, the waveform of the natural acoustic emissions reflects more accurately the damping characteristics of the wood than does the waveform generated by the high "Q" transmitting transducer of the AET 206AU.

A second reason that the AE generated slope is steeper is that the natural AE waveforms have a broad distribution of energy as opposed to uniform pulses for the SWF transmitting transducer. For natural emissions and a given high trigger level, only a small percentage of events will have sufficient energy to be recorded. For a low trigger level, however, most of the emission events will have sufficient energy to be recorded. The difference between the number of counts at the high trigger level and the low trigger level will be great. The pulser transducer method of the AET 206AU generates uniform bursts of energy. In this case, for example, since the pulses are so uniform all pulses will register at the high trigger level as well as the low. The fact that more counts are recorded at the low trigger level reflects only the exponential damping of the waveform and is not also an indication of
events of different energy as are the natural emissions. Therefore the difference in counts recorded for the high and the low trigger levels will not be as great as for the natural emissions, and consequently the slope of the curve plotted from this data will not be as steep.

In summary, the AE themselves are a source of sound within the sample and can be used for measurements of sound attenuation just as is the driving transducer of the AET 206. The attenuation of sound within the material exponentially dampens the AE in the same way as it does for the AET 206 driving transducer. By setting several trigger levels and counters to monitor the AE from the sample, the damping factor for the sample can be determined just as with the AET 206AU. The importance of this is one of economy; it can reduce the cost of instrumentation.

**Small Step RH Experiments**

Most of the work on this project was really preliminary work directed to explore the fundamental issues associated with the development of closed loop control of hardwood drying based at least partly on the monitoring of acoustic emissions. While the work did progress to the point of achieving a laboratory demonstration of such a control strategy, it was realized that additional work was required to make the technique practical. One of the issues was to acquire an understanding of the dynamics associated with the AE for different drying conditions and also for changes in drying conditions. The discussion so far describes various experiments that sought to acquire this information. These experiments started with crude work to simply demonstrate that the rate of AE can in some way be correlated with drying conditions. The work progressed to explore the response to large step changes in an environment that was controlled and closely monitored. These experiments with large step changes gave
good information, but they had practical shortcomings. First, in a practical drying run the environmental conditions do not experience such large step excursions. The conditions are typically changed in small steps, and the goal of an improved control strategy is to change the environment continuously so that there are really no discernible steps. For such a controller, the response to small changes need to be monitored as the feedback. In addition, the AE rate response from wood during drying seems to be non-linear. The response is simply much greater and much quicker for large environmental changes than for small changes. This non-linearity probably varies considerably from sample to sample and also varies as the samples progress to lower moisture contents during drying. So, for purposes of developing a controller, it became apparent that it was necessary to study the response of AE rate to small step changes in environmental conditions.

An experiment was done using matched samples of red oak prepared using the method described above. One sample was equipped with two AE transducers mounted on opposite sides so that both SWF and AE rate could be monitored. The pulser for the SWF measurement was an AC175L. The second sample was equipped with only a single AE transducer. The transducers used on the two samples to monitor AE were AC75L devices from AET. The experiment started with the goal of calibrating the two AE transducers to see how well that they could be matched. For this first part, the conditions were held constant with a mild drying environment, 25 C dry-bulb and 21 C dew-point to give a RH of about 83%. The purpose of using such a mild environment was to achieve a count rate that was not changing much over time for the constant environmental conditions. A more severe environment, if held constant, would produce a count rate that decreased with time. After a few days the AE response of both transducers had stabilized and the gain of one amplifier was varied to
give a count rate that was virtually the same for both transducers. The trigger level for the comparators was also adjusted during this phase to give an additional margin above the background noise level of the electronics. The trigger level referenced to the input of the pre-amplifier was 8.2 microvolts with about 4.8 microvolts of hysteresis. As noted, the total amplifier gain was 100 dB. After everything was stabilized, the dew-point temperature was decreased by 1 C which lowered the RH by about 2.5% to 80.5%. The AE rate was monitored for several days. Figures 4-10 and 4-11 give the AE response for the two transducers. Note that the curves start about 72 hours before the step change to give an indication of how constant the AE rate was before the change. After the step change the AE rate rose from about 3000 CPM to a peak of about 6700 CPM within 6 hours. The rate then decreased to about 4000 CPM after about 50 hours and then rose again to about 5000 CPM before again dropping. This second rise in AE rate was unexpected since the environmental conditions had been held constant. This type of oscillation is typical of second order and higher dynamic systems, but at the time it was felt that the wood drying system was only first order.

At about 140 hours after the first step change in dew-point temperature, the dew-point was decreased by an additional 1 C which lowered the RH to about 78%. This time the response was less than that for the first step change. The AE rate increased from about 3500 CPM to about 4500 CPM within about 8 hours. It should be noted that the response curves for the two transducers on the two separate wood samples was virtually identical. At this point the run was terminated and the sample was sliced up to measure the m profile of the ends. The curve for this data is given in Figure 4-12. Note that the longitudinal m gradient was shallow, varying between about 19% at the end to a maximum of 29%. There were no visible checks anywhere in the samples, which reflects the mild environmental
Fig. 4-10. Small step response, T1.
Dry Bulb Temperature = 25 C  
AET AC75L Transducer  
AE Trigger = 8.2 Microvolts

Fig. 4-11. Small step response, T2.
Fig. 4-12. Moisture content profile of small step sample.

Note: There were no visible checks anywhere.
conditions. Several things are noteworthy for this experiment:

1. Matched wood samples exposed to the same environmental conditions give similar AE responses.
2. Even mild drying conditions give an AE response that is easily detectable.
3. The response to environmental changes decreases as the sample dries, which verifies previous experiments. Note how the peak for the second step change was much lower than for the first step change.
4. The AE rate response to a step environmental change is one that is characteristic for a damped second order system or higher. This is important for development of a control routine.

Some additional work was done to explore the possible sources of the second order dynamic response of the AE rate to the step change in environmental conditions. This work is described in the following chapter.

**Full Size Lumber Drying Experiment**

An experiment was done in a small commercial kiln with full sized lumber as a check to determine if the data for the short samples was really applicable to a real world drying situation. Note that the kiln had a single large fan. The direction of this fan was periodically reversed, as is common in commercial drying, to help the wood to dry more uniformly. The AE count rate was comparable to that in the small chamber experiments. It was also possible to discern when the fan changed direction by the change in AE count rate.
V. Discussion of Experimental Results

Energy Considerations

This project is primarily concerned with control of a flow of energy used to dry hardwood lumber. Energy is input to the wood as thermal energy. The energy either exits the wood again as heat of vaporization of the water exiting, or it is stored within the wood as hygroscopic energy and elastic strain energy within the wood fibers. It is the relatively small amount of energy stored as elastic strain energy that presents the difficulty in drying hardwood lumber without unacceptable checking damage. It was found that AE can be used to monitor damage caused by the large stresses generated by the storage of excessive elastic strain energy in the wood fibers. This information gained from monitoring AE can then be used as an aid in controlling environmental conditions within the kiln, and therefore the rate of energy flow into the wood. A number of experiments were done in which the drying environment was controlled and the resulting AE data monitored or used as a control variable.

Early experiments were done at constant temperature with the flow of energy into the wood controlled by varying the RH. At first this was done by simply exposing the samples to room air (which is at a relatively low RH) or by wrapping the wood sample in plastic to raise the RH (in response to the water evaporating from the wood being contained within the small space enclosed by the plastic wrapping). These simple experiments demonstrated that the rate of AE is increased by lowering RH and is decreased by raising RH. Increasing RH slows the rate of drying, the development of the shrinkage gradient, and therefore the rate of energy being input to the wood and stored in the wood fibers as strain energy.
This simple experiment was repeated in a small kiln in which the RH as well as the corresponding changes in AE activity could be monitored. Similar results were obtained, except for the amount of time that was required to effect the changes in environmental conditions. With the small conditioning chamber used in these experiments the drying conditions could not be changed as rapidly as was the case for changing conditions by manipulating a plastic wrapping. The conditioning chamber required about two hours to reduce the RH from a maximum to a minimum at constant temperature because it required cooling a large water bath using a refrigeration system. The refrigeration system did not have the capacity to cool the water bath quickly. In general, the rate of AE followed this time frame. The conditioning chamber had more capacity to heat the water quickly, and the drop in AE rate was correspondingly more rapid in response to the rapidly increasing RH. This experiment was repeated several cycles on the same sample of wood, and it was found that the time required for the rate of AE to respond to decreasing RH was increased with each cycle, and that the peak rate of AE observed also decreased. It is believed that this is a result of the Kaiser effect. With each cycle the sample had been drying for a longer total amount of time than for the previous cycle and the moisture gradient was subsequently developed more deeply into the wood. It therefore required longer on each succeeding cycle for the moisture gradient to develop sufficiently for the resulting stresses to build up to the level to produce AE. The time span from the change in RH to the resulting change in AE is termed "dead time" for the controller. This dead time does not indicate that the m is not changing within the wood, for the change in m begins immediately with the change in RH. Dead time is simply the time required for the m to change sufficiently to result in a measurable change in the rate of AE. This characteristic of the response of AE to dynamic changes in the drying environment is one of the parameters that a successful
controller must be able to compensate for, and is a reason for the usefulness of a model to describe the dynamic response.

The next step was to try to maintain a constant rate of AE with closed loop control over the drying environment. The variable controlled to maintain a constant rate of AE was the dry-bulb temperature. For a constant water bath temperature, the RH could be decreased by increasing the dry-bulb temperature. At first this met with poor success but adjustments to software control constants corrected the situation for later experiments. The poor initial success was caused by improperly set gain constants in the control equation. The setpoints for environmental conditions were changed too much in response to the amount of error between the AE setpoint and the measured rate of AE. Indeed, it was found that the setpoints for environmental conditions were changed at a rate too great for the conditioning chamber to keep up. This resulted in a phase lag of the environmental conditions behind the setpoint for the conditions set by the control equation. This phase lag resulted in an instability in the rate of AE. After changing the constants in the control equation to values more appropriate it was found that the AE rate could be held fairly constant and stability maintained. Compensation was not done during these experiments, however, for the changes in sound attenuation with temperature. Subsequent experiments varied the RH at constant temperature to eliminate the effects of the temperature variable on sound attenuation. There is no fundamental reason that the change in sound attenuation cannot be compensated for if the controller is capable of measuring sound attenuation. Experiments to measure the change in sound attenuation were done in later experiment using commercial instrumentation, the SWF instrument. Experiments with a commercial instrument, the SWF analyzer, demonstrated an ability to conveniently monitor the changes in a
sample's sound attenuation properties. Changes in sound attenuation affect the meaning of the AE data and must be compensated for in any practical controller based on the monitoring of AE. In wood, changes in sound attenuation can come from many variables such as changes in sample temperature, changes in sample m, and accumulated checking damage. Experiments were done primarily to explore the feasibility of compensating for changes in temperature only, and it was found that this seems practical. Time did not permit detailed exploration of the ability of the SWF instrument to monitor changes in sound attenuation with changes in sample m, although this is not expected to present any great difficulties. One disadvantage of the SWF instrument is that the results of measurements are highly dependent on the settings chosen for the instrument. These settings include the amplifier gain, the trigger setpoint for detecting waveforms from the transducer, the repetition rate of the pulser, and the time window for counting the waveform peaks. This problem could certainly be diminished by simple standardizing on instrument parameters and calibrating the instrument. An alternate method was experimented with to indicate sound attenuation within the sample using the AE as the excitation for the measurement instead of the pulsing transducer used in the SWF instrument. This technique effectively measured the damping characteristics of the sample by comparing the number of AE counts for several settings of the trigger level of the comparators, and seems to be a promising low cost method of measuring the changes in sound attenuation in the wood samples.

It is hoped that additional research will enable the SWF instrument to provide a correction factor to compensate for changes in sound attenuation so that the rate of acoustic emissions can be used to deduce the actual rate of damage to the sample boards. It is possible that the functional performance of the AET 206AU can be gained in a

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different and much less expensive way. The attenuation of sound in a material results in exponential damping of the waveform. It may be possible to use a single AE transducer and amplifier with several electronic comparators set to trigger at different voltage levels to indicate damping in the material. By comparing the number of counts at one trigger level to the number of counts at another trigger level, it may be possible to deduce the damping or sound attenuation properties of the material. This technique would in effect be using the acoustic emissions themselves as the driving signal for the evaluation. A short experiment was done to evaluate this technique by varying the amplification of the acoustic emissions, which is equivalent to changing the trigger level of the comparators. The results of this experiment look promising. A discussion of the results is given in Chapter 4.

One issue which complicates the problem of writing software implementing control of hardwood drying based on the rate of AE is the fact that AE is a non-linear function of the water mass flow rate from the wood. For mild drying conditions the AE rate may be a reasonable low number, but some disturbance that drops the RH significantly for even brief periods of time can increase the AE rate to enormous values. Since the control algorithm is based on the difference between the measured rate of AE to a preselected setpoint, the resulting correction to the drying environment can be so large as to be unreasonable and require a long time to stabilize. A short experiment to test a way to handle this problem was done and seemed to give good results. The proposed solution is to base the control algorithm on the logarithm of the AE count rate. This makes it possible for the controller to have good sensitivity to small errors in count rate but does not allow large AE rate errors to unduly disrupt the controller. It in effect linearized the AE rate to reflect the rate of
energy being dissipated in the microfailures which produce AE. Additional investigation of this technique is recommended for future work.

**Small step dynamic response**

Following the studies for response to large step changes in drying conditions, early closed loop control experiments, and studies on the practicality for monitoring changes in sound attenuation, it was desired to refine the understanding of the dynamic response of AE rates to environmental changes. This is an important part of the study because the environmental conditions will typically be changing at a slow rate in a practical kiln and the changes will be done in small incremental steps. A knowledge and understanding of the dynamic response is critical to achieving an optimal controller. In pursuit of this goal, experiments were done to study the AE response of the wood to small step changes in environmental conditions. The results were somewhat surprising. First, the time response to the change in conditions was much slower that was expected. Typical response to large step change in drying environment resulted in an AE maximum response with one or two hours. It was found that with small step changes that several times as long were required for the rate of AE to reach a peak and drop back to a lower rate. Second, the AE response curve indicated second order characteristics. In other words, the AE rate oscillated, although at a slow rate. It was expected that the rate of AE would first increase to some maximum value and then decrease over time to steadily lower rates. It was found, however that the rate of AE, after increasing to a maximum value and decreasing, actually increased again of its own accord. This indicated that at least two mechanisms of energy storage were interacting to affect the rate of AE. It is important to understand this behavior since it could easily confuse a computer controller.
Acoustic emissions give information on the state of stress in wood that result from the shrinkage gradient that occurs during drying. The end goal is to dry the wood as rapidly as possible without generating stresses so great that the damage to the wood is excessive. The additional information obtained by monitoring AE can be used to improve control over the drying process. However, new techniques are required to enable effective use of this information, as noted below.

In order to achieve optimal control of a process, it is first necessary to have a model of the system under investigation. It is not necessary that all elements of the system be modeled. For example, to implement a PID algorithm it is necessary to know the system time constant and gain. For acoustic emissions, the gain might be expressed in counts per minute per unit change in drying conditions. This gain, however, depends not only on the attenuation of sound in the material but also on the particular temperature at which the control process is being done. In addition, the rate of acoustic emissions is a non-linear function of the level of stress; the material stress can be continuously increased without producing AE until some stress threshold is encountered, at which point the material begins to fail and then produce AE.

When the study began, it was assumed that the system under investigation had simple first order dynamic characteristics. Such a system could be modeled as a capacitor being discharged through a resistor with a back emf to control the rate of discharge. This is an electrical analog of the water mass flow in the system. The capacitor here is analogous to the water storage capacity of the wood, the charge on the capacitor represents the water mass stored in the wood material, and the resistor illustrates the resistance to water flow through the wood. This flow resistance is inversely proportional to the
wood's moisture diffusion coefficient. The back emf illustrates the drying conditions of temperature and relative humidity which can be adjusted to change the rate of drying. For example, if the potential on the battery is equal to that on the capacitor, then no current flows. Similarly, if the relative humidity in a drying chamber is at 90%, then the wood cannot dry to a lower moisture content than its EMC at the given temperature and RH. This phenomenon is well documented.

Such a system gives predictable response to inputs. For example, if the potential in the battery is dropped in a step change, the current will follow an exponentially decaying rate. This is typical of all first order systems, electrical, mechanical, or wood moisture movement. However, it does not adequately describe the acoustic emissions data that was recorded for a step change in drying conditions. A more in-depth analysis of the system demonstrates that the simple mass flow analogy is inadequate and that in order to give a more realistic representation it is necessary to model the energy of the system.

It is possible to deduce a great deal of information about any dynamic system by giving it a step input of energy and observing the response. For an electrical system, this might be a step change in voltage. For a mechanical system, it might take the form of a step change in force. The wood system was really somewhat of an unknown as to the energy storage elements and the dynamics as they relate to the rate of AE.

Early attempts at closed loop control of the drying process based on controlling the rate of AE were met with poor results. The problem was a poor understanding of the dynamics involved. As indicated in the preceding chapter, it was observed that the rate of AE was a strong function of the drying conditions. For example, if the system was held at constant drying environmental conditions for a length of

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Discussion of Experimental Results
time, perhaps a day or two, then the rate of AE would stabilize at some constant rate, perhaps 2000 CPM. If the conditioning chamber door were opened suddenly, which resulted in a rapid large drop in relative humidity, then the AE count rate would rise rapidly, perhaps to 100,000 CPM and would reach this count rate within two or three minutes. Therefore it was concluded that the system had a rapid time response and the control loop was adjusted to change the drying conditions every 10 minutes. Several runs were done to experimentally determine the controller gain required to maintain a constant count rate. The controller gain in this case is the change in relative humidity or temperature that is required to correct for a given error in AE count rate. The first several attempts at AE based closed loop control of drying resulted in an unstable control system because the controller gain was set too high. Eventually, however, stability was achieved and a sample was dried at a relatively constant count rate.

A more detailed study was then done to evaluate the factors that affect the count rate. An AET 206 was used to give an indication of the attenuation of sound in the wood. This led to conducting many of the experiments at constant temperature to eliminate this variable from the problem. Relative humidity was adjusted as the only parameter to control the count rate. Finally, the system was given some small step changes in drying conditions. The system response was much different for small than for large step inputs. For the small step changes, the time response was on the order of 30 hours, not the minutes that had been observed for the large inputs. In addition, as illustrated by data in Figures 4-10 and 4-11, the count rate slowly oscillated. This led to some additional considerations on the model for the system that will now be discussed in greater detail.

Chapter V  
Discussion of Experimental Results
A block diagram is given in Figure 5-1 to illustrate a proposed model of the energy flow during drying and the associated controller with instrumentation feedback. In the figure, heavy lines indicate energy flow and thin lines indicate data flow. As indicated, the controller is first setup with the desired wood m endpoint and also the measured initial wood m. The air temperature and RH is then controlled by the innermost feedback loop. By heat transfer, energy is input to the wood from the the air resulting in water mass transfer. Most of the energy input to the wood exits as heat of vaporization when the water evaporates from the wood. A significant amount of energy is stored within the wood cellulose in the form of hygroscopic energy when the wood fibers dry to a lower m. A much lesser, but very important component of energy is stored as elastic strain energy resulting from the gradient of wood m. When the stresses in the wood fibers become too large, the wood undergoes small fractures releasing acoustic energy which can be measured by suitable AE instrumentation. This AE rate is the basis of the second controller feedback loop. As indicated by the data described in Chapter 4, the AE rate can oscillate slowly after a step change in drying conditions. It is proposed that energy can be exchanged within the wood between the elastic strain energy and the hygroscopic energy, as is illustrated by the coupling in Figure 5-1. The most probable mechanism for this is the hygroelastic effect [44], by which mechanical stresses change the EMC of the wood. Tensile stresses at the ends of a sample would increase the EMC, and relaxation of the stresses during creep would have the opposite effect. Finally, as a result of water exiting the wood, the wood m decreases and can be measured with suitable instrumentation. This data is fed back to the controller to indicate when drying is complete. A model is derived in the following chapter to support this proposal for energy flow within the wood.
Fig. 5.1. Drying system overview.
VI. Dynamic Model

The rate of drying is controlled by varying the relative humidity and temperature of the air surrounding the wood. Environmental changes must be made often during the drying process, and this results in changes in the rate of AE. As illustrated in the preceding chapter, the rate of AE is not a linear function of the drying environment and in addition can slowly oscillate as a result of a small step change in the drying environment. A computer controller must be able to compensate for this type of dynamic response to remain stable and produce optimal results. This chapter discusses the dynamics involved and proposes a simplified second order model for the system.

For many systems the identity of system elements is quite obvious. For example, an electrical system has inductors and capacitors that store energy and resistors that dissipate energy. An analogous mechanical system has masses and springs that store energy and dampers that dissipate energy. If a system has only one energy storage element such as a capacitor it is a first order system. If it has two different types of storage elements, such as both a capacitor and an inductor it is a second order system. It is generally easy in electrical and mechanical systems (at low frequencies) to identify the system elements and to model the systems. Many systems that must be controlled do not have elements that can be readily identified, and the control coefficients must be derived from observations of the system response to known inputs. Chemical systems with varying rates of reactions are commonly in this class of system.

The first step in working toward a system model is to observe that some measurable output, such as AE rate, is a function of some controllable input, in this case relative humidity. Experiments have
indicated that this is true.

The second step is to identify the elements of the system. For drying wood, this is commonly held to be a capacitance of moisture storage that is discharged through a resistance to water flow that is inversely related to the permeability of the wood. However, this model predicts a first order response, which is true for the rate of drying, but does not adequately describe the rate of AE. A more in-depth study of the wood system reveals additional energy storage elements. One of these energy storage elements is storage of thermodynamic energy in the specific heat of the water in the wood. Since the system under study could be held at a constant temperature, this was eliminated as a factor. A second energy storage mechanism is the energy stored as chemical energy by the bonding of water to cellulose in the wood fibers or hygroscopic energy. A third energy storage element is the energy stored as elastic strain energy (both tensile and bending) in the wood fibers as the wood experiences a shrinkage gradient during drying. Second order type response was observed in the count rate, but it was not obvious how the energy storage elements interacted. The chemical energy described above is a capacitive type of energy storage and the elastic strain energy of the wood fibers is a spring type of energy storage. A spring is the mechanical analog of a capacitor. The problem is that two capacitors interacting are still a first order system, two capacitors can not oscillate and they cannot experience the second order type of overshoot that was observed.

There are some fundamental characteristics about a second order system and the energy storage elements that allow it to oscillate. It is not necessary that the energy storage elements be all of one system type, for example all electrical or all mechanical in order to result in second order type behavior. It is quite possible for elements of an

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electrical system to interact with a mechanical system as in an electric motor. The characteristics of the system that make it second order are fundamental in nature. The basis of it is that one of the energy storage mechanisms must be time dependent and the other position dependent. Systems can be expressed in terms of generalized coordinates that consider only the energy stored and not the particular nature of the elements storing the energy. All systems can be expressed in terms of time and a generalized position and generalized velocity. The system equation can then be derived using the Lagrangian [45].

A close examination of the wood drying system reveals that it is also a dynamic second order system. A wood sample was subjected to constant drying conditions for about two weeks and then was given a step change in drying conditions in order to study the time response of the acoustic emissions. Figures 4-10 and 4-11 illustrate the results. Note that, previous to the step change in drying conditions, the count rate had been constant for more than a week. After the step change in conditions, which was a drop in relative humidity of about 2.5% at a constant temperature, the AE rate exhibited the type of time response behavior common to underdamped second order systems. The time constant of the system is about 60 hours and the damping factor is about 0.4. The system gain is about 1000 counts per minute per 1% change in relative humidity. These parameters are expected to vary as a function of moisture content, temperature, and of course damage that would increase sound attenuation.

Returning now to the problem of modeling the system and the two energy storage elements that have been identified, chemical energy of water adsorption and the elastic strain energy of the wood fibers as a function of the moisture gradient. Proceeding with the Lagrangian analysis, it is apparent that the energy storage mechanism in the

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moisture capacitance is not a function of time. Therefore the mass of water per unit volume of wood is taken as the generalized position coordinate. The elastic strain energy storage is clearly dependent on the moisture gradient which is in turn dependent on the rate of water mass flow in the wood. Therefore the elastic strain energy storage mechanism is a function of time and is the generalized velocity coordinate for the Lagrangian. This term is dependent on the geometry, diffusivity and modulus of elasticity of the sample.

This energy storage is small in magnitude but is significant when attempting to control the drying process based on the rate of acoustic emissions. The issue is that a small step change in drying conditions produces a resulting change in the rate of acoustic emissions that may require days to reach equilibrium. Any computer based controller must have compensation to remain stable and to produce the desired results. It is proposed that the energy storage mechanisms within the wood form a second order system (low Q) that can result in the rate of acoustic emissions slowly oscillating.

The second order system is formed by the elastic strain energy and the hygroscopic energy. The elastic strain energy that is modeled is the cantilever spring energy stored by the wood fibers at the end of a sample being bent in response to the moisture gradient at the end of the sample. The hygroscopic energy is the well known energy stored in chemical form as water is removed from wood that is below the fiber saturation point. The equations are derived in a way that depend on the moisture per gram of wood and the mass flow rate of moisture per gram of wood. Mass flow rate is used instead of the more familiar moisture gradient in order that the resulting differential equation can be put into a standard form and therefore use methods of analysis that are common with dynamic systems. An example is
the determination of the period of oscillation.

The concept of the Lagrangian is used to derive the differential equation. The Lagrangian is given by:

$$\mathcal{L} = T - V$$  \hspace{1cm} (6.1)

where:

- $\mathcal{L}$: For a system, the time-dependent energy storage minus the time-independent energy storage
- $T$: Time-dependent mechanism of energy storage
- $V$: Time-independent mechanism of energy storage

Lagrange's equation, which describes the energy in a system, is given as follows [45]:

$$\frac{d}{dt} \frac{\partial}{\partial \dot{m}} \mathcal{L} - \frac{\partial}{\partial m} \mathcal{L} = 0$$  \hspace{1cm} (6.2)

Strain energy, from Eq. A.10, is given as:

$$T = \frac{5}{39} \frac{E h^4 \rho_< \rho_{\text{wood}} s^2_{\text{max}}}{K_{\text{cond}}^2 \Delta m^2_{\text{max}}} \dot{m}^2$$  \hspace{1cm} (6.3)

The symbols are as follows:

- $T$: elastic energy storage, with units of $\text{Joules/Kg-wood}$
- $h$: is half the width of the sample, or 50 mm, assumed to be in the tangential direction

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Dynamic Model
\( \rho_{\text{wood}} \) the density of the wood

\( s_{\text{max}} \) the maximum possible dimensional shrinkage in the tangential direction

\( \Delta m_{\text{max}} \) is the maximum change in wood moisture content, from fiber saturation to dry

\( m \) the rate of change in moisture content.

Values for constants are given in Table A-1.

The other energy term is given as follows from Eq. A.12:

\[
V = e^{11.18 - 12.45 m}
\]

\[
V \quad \text{hygroscopic energy storage, with units of Joules Kg-wood}
\]

Note that \( m \) is the sample moisture content.

The linearized differential equation, as given in Eq. A.29, is:

\[
\frac{10}{39} \frac{E h^4 \rho_{\text{wood}} s_{\text{max}}^2}{K_{\text{cond}}^2 \Delta m_{\text{max}}^2} \; m_1 - S_{dhw,m} \; m = 0
\]

Where the constant \( S_{dhw,m} \) is the slope of the differential heat of wetting curve. At a moisture content of \( m = 0.2 \), it is given by:

\[
S_{dhw,2} = -9.21 \times 10^5 \frac{J \text{ Kg-wood}}{\text{Kg-water}^2}
\]
Note that $S_{dhw,m}$ is negative, which results in a positive sign between terms of Eq. 6.5.

The time dependent energy storage term is the elastic energy storage in the bending of the wood fibers. The mass flow rate from the end of the sample is associated with a moisture gradient in the wood at its end. The moisture gradient, when below the fiber saturation point, has a corresponding shrinkage gradient. It is the shrinkage gradient that puts the load on the wood fibers and causes them to bend and store elastic strain energy. Since the energy is stored in a spring, it is a potential energy storage mechanism. However, since the amount of energy stored is dependent on the mass flow rate of water, it is a time-dependent potential energy storage. (It is analogous to the energy storage in the magnetic field of an inductor. The magnetic field is a potential energy storage but it depends on the rate of flow of electrons through the winding of the inductor, which make it a time-dependent potential energy storage.) The model only considers the energy stored in the bending of the wood fibers at the end of the sample. The model assumes that the only moisture flow from the wood is out the ends and therefore ignores any energy stored in tension due to a moisture gradient perpendicular to the axial direction. The model also only considers energy stored in the wide direction of the sample (the 100 mm dimension) since it is this direction that will result in the largest stresses that produce acoustic emissions. For analysis purposes it is assumed that the fibers bend toward the center, and so the 100 mm dimension can be split into two sections, each of which are 50 mm by 50 mm. Only one of these sections is modeled since symmetry is assumed. The loading is assumed to increase parabolically from zero load at 150 mm from the end to a maximum at the end of the sample. The load is assumed to be uniform perpendicular to the axial direction to simplify the model. Also, the permeability of the wood to moisture

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*Dynamic Model*
flow is assumed to be 35 times that of gross wood. This is reasonable for short lengths of red oak.

For the time-independent energy storage, or hygroscopic energy, another set of assumptions are used. First, the variation along the length is not modeled. This is a lumped parameter model. To consider the variation of moisture content along the length of the sample would have required a much more complicated distributed parameter model. The variation of heat of wetting with moisture content is modeled, although the function must be linearized at the $m$ of interest to calculate the period of oscillation.

Again, this is not an exact model and it makes many simplifying assumptions. It attempts to make reasonable tradeoffs and still meet the objective of modeling some of the data that was recorded and to give a basic model useful for automatic control of drying red oak based on acoustic emissions.

Period of oscillation, $\tau$, from Eq. A.30, is given by the following:

$$
\tau = 2\pi \left( \frac{10 E h^4 \rho_{\text{wood}} s_{\text{max}}^2}{39 K_{\text{cond}}^2 \Delta m_{\text{max}}^2 - S_{\text{dhw.2}}} \right)^{\frac{1}{2}}
$$

(6.7)

Where $S_{\text{hw.2}}$ (Eq. 6.6) is the coefficient for the slope of the linearized differential heat of wetting curve at a moisture content of 0.2. The final result, from Eq. A.31, is:

$$
\tau = 61 \text{ hours}
$$

(6.8)
This value for period of oscillation is in agreement with the data given in Fig. 4-10 and Fig. 4-11.

Note, the above oscillation of mass flow rate is about some average. It is known that stresses and therefore AE are a result of the shrinkage gradient associated with the mass flow rate. The maximum mass flow rate and therefore maximum rate of drying is limited by the amount of energy that can be stored as elastic energy before fractures occur.

Assumptions
The following assumptions were used in the analytic model of the drying system.

1. The sample is a rectangular solid. Only the strain energy in the wide dimension is considered.

2. The entire sample is below the fiber saturation point and moisture content varies only in the outer 150 mm of the sample length.

3. All processes occur at a constant temperature.

Figure 6-1 gives an analogous electrical circuit for the wood drying system in order to increase understanding. Note that it has a capacitor that is initially uncharged which is charging through an inductor. The inductor represents the time dependent strain energy of the wood fibers and the resistor represents the various energy dissipative elements. Some of the energy dissipators are the loss of energy from the wood fibers when the wood fractures to generate the acoustic emissions and also such energy dissipators as creep in the wood. The battery, whose potential is initially the potential of the
Note: Energy lost from the system for water evaporation is not shown.

Rate of drying is limited by the amount of energy that can be stored in this element. AE is an indicator of the energy lost from the element during material failure.

Fig. 6-1. Model for energy flow.
capacitor is varied to control the flow of current into the charging capacitor. This is analogous to the potential for drying that is presented by the temperature and humidity in the conditioning chamber. Just as a higher potential on the battery of the electrical circuit can increase the flow of current for the electrical circuit, a lower humidity can increase the rate of heat energy flow into the wood sample and the corresponding flow of water out of the sample.

An additional analog for the inductor and the elastic strain energy of the wood fibers. If the flow rate of moisture is too great, as in a drying environment that is too severe, the wood fibers will fracture resulting in irreversible damage. For some ferrite materials used in the manufacture of inductors, a current flow that is too great will create a magnetic field that is too strong and result in irreversible damage to the ferrite.

It is interesting to consider the amount of energy storage in the wood system. There is energy stored as thermodynamic energy in the water as enthalpy. However, to remove the water from the wood, an amount of energy must be added to the wood that is equal to the heat of vaporization of the water. For the elastic strain energy, the limit is the amount of energy that can be stored without exceeding the tensile strength of the wood. The result, shown in Appendix A, is that the amount of energy that must be added to the wood in the form of heat energy is about 11,000 times the amount of energy that can be stored in the wood fibers as elastic strain energy (see Eq. A.81). This is one reason that the wood is so easily fractured.

Another circuit analogy can be used to explain other observed behavior in the wood. Recall that for a large step change in the drying conditions that the AE rate changed rapidly and that for a small step
change the AE rate responded with a slow time constant. This is related to the non-linear nature of the acoustic emissions response to mechanical stress. At zero stress, there are no acoustic emissions from a material because there are no fractures. As the stress level is increased, there are no acoustic emissions until a critical value of stress, the fracture strength of the material, is exceeded. This is a non-linear response. A large signal response will take the material through this stress transition region rapidly giving the system the appearance of a short time constant. A small signal input will on the other hand, make the transition through the critical stress region over a much longer period of time giving the system the appearance of a much longer time constant.

There is an an additional interesting analogy that should be noted. Since the water is acting like a capacitive time-independent energy storage and the strain energy is acting like a time-dependent energy storage inductive element, the spring of the wood fibers is actually behaving as a mass in a mechanical system. An additional note is that the energy of a mass is a kinetic (time dependent) energy storage. However the energy storage in the wood fibers is a potential energy storage, but is actually a time-dependent potential energy storage. In this respect the wood is behaving more similarly to the electrical circuit analogy. The reason for this is that the energy storage in an inductor is also a time-dependent potential energy storage. The potential energy here is in the magnetic field of the inductor. The magnetic field in this case is the result of the time rate of electron flow through the wire of the inductor. This is the primary reason for selecting the electrical circuit analogy for the wood system instead of a mechanical system analogy.

It is not really possible to reflect the true complexity of the wood
drying system with a simple circuit analogy, even one with many components. One of the energy mechanisms that has no electrical analog is the energy that goes into the phase change of the water. It is also difficult to model the orthotropic nature of the wood. The wood has a complicated structure that affects both the flow of water and also the mechanical properties.
VII. Conclusions

It was found that AE gives a rapid and sensitive indication of failure inducing stress in wood samples during drying. This internal stress, which is a result of differential shrinkage from moisture gradients developed during drying, must be kept below the threshold which results in unacceptable damage. Monitoring AE gives information on the magnitude of this internal drying stress that is not obtained with conventional drying technology. In addition, monitoring AE gives a near instantaneous indication of changes in the state of stress that may be useful for optimizing the rate of drying for a given rate of checking damage. It was found that commercial instrumentation is sufficiently sensitive to easily measure AE for rates of damage so low that no visible damage results in the wood samples.

There are many process variables that can distort the measurements of AE. However, there are methods available that allow compensation for the interferences. It was found to be convenient to eliminate acoustical noise interferences such as fans, air flow, etc., by simply using resonant transducers and limiting the bandwidth of the amplifiers. Interferences related to changing sound attenuation properties in the wood samples were found to be significant. Commercial instrumentation was used in experiments which demonstrated the feasibility of detecting changes in sound attenuation for changes in temperature. This same technique should also be able to measure changes in sound attenuation from other causes such as changes in $m$ and also accumulated checking damage. An alternate measurement technique giving a similar sensitivity to changes in sound attenuation was explored which could be implemented with less expensive instrumentation. These techniques were studied but were not implemented in the software for closed loop control.
Additional data must be collected before these compensation techniques will be sufficiently robust for practical use.

A strong correlation was observed between the rate of AE and the rate of checking damage, although this was not proven with statistical techniques. Low rates of AE resulted in little or no checking damage during a period of one week whereas high rates of AE resulted in visible damage within a few hours. It was demonstrated that the drying process could be controlled by a computer programmed to vary environmental conditions to maintain the rate of AE at a preset value.

It was found that the rate of AE slowly oscillates in response to small step changes in drying conditions. The system of energy storage within the wood which produces the drying stresses resulting in acoustic emission was modeled using the Lagrangian. Energy storage mechanisms within the wood were found to interact in a way that directly affected the dynamic response of AE to changes in drying conditions. These energy storage mechanisms were found to be the hygroscopic energy and the elastic energy storage of the wood fibers as they bend in response to moisture gradients at the ends of the samples. The energy storage was found to be an underdamped second order chemical-elastic system. The model predicted a period of oscillation of about 61 hours for the system and this was in reasonable agreement with the measured data for response to a small step change in relative humidity. This model is intended to increase understanding of the AE response during wood drying and can be used by future computer programs to set control constants in PID algorithms, and therefore give more stable and accurate control.

In summary, AE from wood drying stresses were investigated and it is believed that they will prove to be a useful supplement to conventional
control methods. It is recommended that additional studies be directed toward gathering some of the unknown functional relationships between acoustic emission and the actual rate of damage in hardwoods. For example, a precise knowledge does not exist for indicating the rate of damage for a given rate of acoustic emission for known sample sound attenuation characteristics. This functional relationship will be time consuming to acquire for it must be done experimentally. Since the drying of a sample of oak can require up to six weeks and a number of samples would need to be dried at various rates of acoustic emission and temperature schedules, the study could take much time if work cannot be done in parallel.
References

Chapter 1


2. Ibid, p. 222-225.


Chapter 2


References


Annual Meeting of the Forest Products Research Society in New Orleans, Louisiana.


Chapter 3

Chapter 5
44. Skaar, 1972, p. 150.

Chapter 6

Appendix A
46. Bodig, p. 669.

47. Siau, Fig.6.9, p.93-94.


51. Shigley, p.124.
APPENDIX A, MODEL DEVELOPMENT
Model Summary

The following model describes the dynamics involved between two energy storage mechanisms during the drying of wood. This energy storage is small in magnitude but is significant when attempting to control the drying process based on the rate of acoustic emission. The issue is that a small step change in drying conditions produces a resulting change in the rate of acoustic emission that may require days to reach equilibrium. Any computer based controller must have compensation to remain stable and to produce the desired results. It is proposed that the energy storage mechanisms within the wood form a damped second order system that can result in the rate of acoustic emission slowly oscillating.

The second order system is formed by the elastic strain energy and the hygroscopic energy. The elastic strain energy that is modeled is the cantilever spring energy stored by the wood fibers at the end of a sample being bent in response to the moisture gradient at the end of the sample. The hygroscopic energy is the well known energy stored in chemical form as water is removed from wood that is below the fiber saturation point. The equations are derived in a way that depend on the moisture per kilogram of wood and the mass flow rate of moisture per kilogram of wood. Mass flow rate is used instead of the more familiar moisture gradient in order that the resulting differential equation can be put into a standard form and therefore use methods of analysis that are common with dynamic systems. An example is the determination of the period of oscillation.

The derivation uses the concept of the Lagrangian, as was described in Chapter 6, to develop the differential equation.

The mass flow rate from the end of the sample is associated with a
moisture gradient in the wood at its end. The moisture gradient, when below the fiber saturation point, has a corresponding shrinkage gradient. It is the shrinkage gradient that puts the load on the wood fibers and cause them to bend and store elastic strain energy. Since the energy is stored in a spring, it is a potential energy storage mechanism. However, since the amount of energy stored is dependent on the mass flow rate of water, it is a time-dependent potential energy storage. The model considers only the elastic energy stored in the bending of the wood fibers at the end of the sample. The model assumes that the only moisture flow from the wood is out the ends and therefore ignores any energy stored in tension due to a moisture gradient perpendicular to the axial direction. The model also only considers energy stored in the wide direction of the sample (the 100 mm dimension) since it is this direction that will result in the largest stresses that produce acoustic emission. For analysis purposes it is assumed that the fibers bend toward the center, and so the 100 mm dimension can be split into two sections, each of which are 50 mm by 50 mm in cross section. Only one of these sections is modeled since symmetry is assumed. The loading is assumed to be parabolic and to be zero 150 mm from the end and a maximum at the end of the sample. The load is assumed to be uniform perpendicular to the axial direction to simplify the model. Also, the effective diffusion coefficient of the wood to moisture flow is assumed to be 35 times that of gross wood. This is reasonable for short lengths of red oak.

For the time-independent energy storage, or hygroscopic energy, another set of assumptions are used. First, the variation along the length is not modeled. This is a lumped parameter model. To consider the variation of moisture content along the length of the sample would have required a much more complicated distributed parameter model. The variation of hygroscopic energy produces a
non-linear differential equation. Therefore, the equation was
linearized at the moisture content of interest, about 20%, to avoid this
difficulty and to make it possible to use standard techniques to
calculate the period of oscillation for the system.

The equation resulting from the model does not have a term for
damping. Physically, this would result in a system that would
oscillate forever which is not possible. Damping in the system is in
the form of material creep as well as energy released in the form of AE.

An effort was not made to generate a model of the AE that would
result from elastic strain energy released from the system.

Again, this is not an exact model and it makes many simplifying
assumptions. It attempts to make reasonable tradeoffs and still meet
the objective of modeling some of the data that were recorded and to
give a basic model useful for automatic control of drying red oak
based on acoustic emission.

The model is developed in the following order:

1. Set up the equation for the Lagrangian.

2. Derive equation for elastic strain energy in the wood fibers at the
   end of the sample resulting from the shrinkage gradient due to
drying. This equation is expressed in terms of mass flow rate of
   water, and uses the diffusion coefficient and moisture content
difference.

3. Derive the slope of the differential heat of wetting curve at a m of
   20%.

Appendix A

Model Development

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4. Insert the above into Lagrange's equation for the resulting differential equation.

5. Calculate the system period of oscillation.

The model is an attempt to derive a reasonable value for the period of oscillation, and so verify that the assumed interaction between hygroscopic energy and elastic strain energy actually occurs. Values for constants used in the calculations are given in Table A-1.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Moisture Flow Area</td>
<td>$2.50 \times 10^{-3}$ m$^2$ (4 in$^2$)</td>
</tr>
<tr>
<td>b</td>
<td>Base of cross section (Thickness of sample)</td>
<td>$5.00 \times 10^{-2}$ m (2 in)</td>
</tr>
<tr>
<td>E</td>
<td>Modulus of Elasticity</td>
<td>$8.96 \times 10^9 \text{ N/m}^2$ (1,300,000 lb/in$^2$)</td>
</tr>
<tr>
<td></td>
<td>from Bodig [46]</td>
<td></td>
</tr>
<tr>
<td>$D_{gl}$</td>
<td>Diffusion coeff. gross wood longitudinal direction</td>
<td>$1.3 \times 10^{-9}$ m$^2$/sec</td>
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<tr>
<td></td>
<td>for Mbar = 22%, 25 C, $G_0 = 0.5$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>From Siau [47]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>assumed effective value</td>
<td>$4.55 \times 10^{-8}$ m$^2$/sec</td>
</tr>
<tr>
<td></td>
<td>(diffusion coefficient assumed to be 35 times value from Siau)</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>Height of cross section (Half of sample width)</td>
<td>$5.00 \times 10^{-2}$ m (2 in)</td>
</tr>
<tr>
<td>$h_{fg}$</td>
<td>Heat of vaporization for water</td>
<td>$2.39 \times 10^6$ Joules/Kg-water</td>
</tr>
<tr>
<td>$K_{cord}$</td>
<td>Conductivity Coefficient</td>
<td>$2.28 \times 10^{-7}$ kg-water/% m sec</td>
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<tr>
<td></td>
<td>(calculated from above assumed $D_{gl}$)</td>
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</tr>
<tr>
<td></td>
<td>Alternate units for $K_{cord}$</td>
<td>$2.28 \times 10^{-5}$ kg-wood/m sec</td>
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<td>(for use in all equations)</td>
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(cont.)
Table A-1. (cont)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{\text{max}}$</td>
<td>Max change in $m$</td>
<td>0.3 $\frac{\text{Kg-water}}{\text{Kg-wood}}$</td>
</tr>
<tr>
<td>$\rho_{\text{water}}$</td>
<td>Density of water</td>
<td>1000 $\frac{\text{Kg-water}}{\text{m}^3}$</td>
</tr>
<tr>
<td>$\rho_{\text{wood}}$</td>
<td>Density of wood</td>
<td>500 $\frac{\text{Kg-wood}}{\text{m}^3}$</td>
</tr>
<tr>
<td>$\sigma_{\text{tmax}}$</td>
<td>Max tensile strength for oak (in tangential direction)</td>
<td>$1.034 \times 10^7 \frac{\text{N}}{\text{m}^2}$</td>
</tr>
<tr>
<td></td>
<td>From Bodig [48]</td>
<td>(1500 $\frac{\text{lb}}{\text{in}^2}$)</td>
</tr>
<tr>
<td>$s_{\text{max}}$</td>
<td>Max fractional shrinkage</td>
<td>0.086</td>
</tr>
</tbody>
</table>
Differential Equation Derivation

The following section derives the system differential equation for the mass flow of water, as well as the period of oscillation. It is assumed that the acoustic emission data recorded was a function of the elastic strain energy in the sample, which is in turn a function of the water mass flow rate. The following section is a summary that uses functions derived later in this Appendix. The primary one that is derived later is the function for elastic strain energy resulting from the moisture gradient at the end of the sample.

The Lagrangian is defined as:

\[ L = T - V \] \hspace{1cm} (A.1)

A system differential equation can be derived using Lagrange's equation as follows:

\[ \frac{d}{dt} \frac{\partial}{\partial \dot{m}} L - \frac{\partial}{\partial m} L = 0 \] \hspace{1cm} (A.2)

First, express the term for the time dependent energy storage, which is the energy stored as elastic strain energy in the wood fibers as they are bent as a result of the shrinkage from the moisture gradient, which in turn is a result of the water mass flow from the end of the wood.

\[ T = u \] \hspace{1cm} (A.3)

The total strain energy storage, which is from Eq. A.60, is as follows:

\[ U = \frac{13}{1620} \frac{L^9 k^2}{EI} \] \hspace{1cm} (A.4)
Need to express this energy in terms of "per kilogram of wood", so divide by volume and density of the wood sample:

\[ u = \frac{13}{1620} \frac{L^9 k^2}{E I V_{\text{wood}} \rho_{\text{wood}}} \]  \hspace{1cm} (A.5)

\[ I = \frac{b h^3}{12} \]  \hspace{1cm} (A.6)

\[ V_{\text{wood}} = b h L \]  \hspace{1cm} (A.7)

And since \( T = u \),

\[ T = \frac{13}{135} \frac{L^8 k^2}{E b^2 h^4 \rho_{\text{wood}}} \]  \hspace{1cm} (A.8)

Note that \( k \) expresses the load function on the wood fibers that cause them to bend. This load is proportional to shrinkage which is in turn proportional to the gradient of moisture content, \( \Delta m \), and therefore to water mass flow rate, \( \dot{m} \).

Now need to express \( k \) in terms of \( \dot{m} \), which is from Eq. A-50:

\[ k = -\frac{15}{13} \frac{\rho_{\text{wood}} E b h^4 s_{\text{max}}}{K_{\text{cond}} L^4 \Delta m_{\text{max}}} \dot{m} \]  \hspace{1cm} (A.9)

Substituting this into Eq. A.8 above gives the time-dependent energy term:

\[ T = \frac{5}{39} \frac{E h^4 \rho_{\text{wood}} s_{\text{max}}^2}{K_{\text{cond}}^2 \Delta m_{\text{max}}^2} \dot{m}^2 \]  \hspace{1cm} (A.10)
Now express the terms for the time-independent energy storage mechanism, which is the hygroscopic energy, \( W \):

\[
V = W
\]  \hspace{1cm} \text{(A-11)}

Note that \( W \) is hygroscopic energy with units of Joule/Kgwood. Note also that for this derivation, \( W \) must be defined as the heat energy that goes into the wood and is stored as hygroscopic energy. From Eq. 2.8 and Eq. A.11, \( W \) is equal to \( V \) and is given by:

\[
V = e^{11.18 - 12.45m}
\]  \hspace{1cm} \text{(A.12)}

The negative of \( V \) is plotted in Figure A-1 since this is the form used in Eq. A.1 for the Lagrangian.

Now must develop the differential equation from Lagrange's equation:

\[
\frac{d}{dt} \frac{\partial}{\partial \dot{m}} L - \frac{\partial}{\partial m} L = 0
\]  \hspace{1cm} \text{(A.13)}

where \( L \) is given as:

\[
L = T - V
\]  \hspace{1cm} \text{(A.14)}

Combining Eq. A.14 with Eq. A.10 and Eq. A.12 gives:

\[
L = \frac{5}{39} \frac{E h^4 \rho_{\text{wood}} s_{\text{max}}^2}{K_{\text{cond}}^2 \Delta m_{\text{max}}^2} \dot{m}^2 - e^{11.18 - 12.45m}
\]  \hspace{1cm} \text{(A.15)}

Proceeding with the first derivative term for Lagrange's equation:
Fig. A-1. Negative of hygroscopic energy curve.
\[
\frac{\partial}{\partial \dot{m}} L = \frac{\partial}{\partial \dot{m}} \left( \frac{5}{39} \frac{E h^4 \rho_{wood} S_{max}^2}{K_{cond}^2 \Delta m_{max}^2} \dot{m}^2 \right)
\]

(A.16)

This gives:

\[
\frac{\partial}{\partial \dot{m}} L = \frac{10}{39} \frac{E h^4 \rho_{wood} S_{max}^2}{K_{cond}^2 \Delta m_{max}^2} \dot{m}
\]

(A.17)

Now develop the second partial derivative for Lagrange's equation:

\[
\frac{\partial}{\partial m} L = \frac{\partial}{\partial m} (e^{11.18 \cdot 12.45 m})
\]

(A.18)

This reduces to:

\[
\frac{\partial}{\partial m} L = 12.45 e^{11.18 \cdot 12.45 m}
\]

(A.19)

Note that \( V \) is analogous to the energy storage in a spring with moisture content \( \dot{m} \) being analogous to the deflection of the spring. In this case the spring is non-linear. The slope of the curve in Eq. A.19 (calculated at the moisture content of interest), is equivalent to a spring constant. The function described by Eq. A.19 is analogous to the force required to deflect the spring.

Note that the function given by Eq. A.19 is non-linear, and when it and Eq. A.17 are applied to Lagrange's equation in Eq. A.13, the result is the following non-linear differential equation for the flow of moisture in the wood:

\[
\frac{10}{39} \frac{E h^4 \rho_{wood} S_{max}^2}{K_{cond}^2 \Delta m_{max}^2} \ddot{m} - 12.45 e^{11.18 \cdot 12.45 m} = 0
\]

(A.20)
In order to calculate a period of oscillation at a given \( m \), the function given by Eq. A.19 must be linearized. This is done by taking the derivative of \( \frac{\partial}{\partial m} L \) (from Eq. A.19) with respect to \( m \) and calculating the value of the slope at the moisture content of interest, which is \( m = 0.2 \). This is similar to a linearization example given by Doebelin [49].

\[
\frac{\partial}{\partial m} \left( \frac{\partial}{\partial m} L \right) = \frac{\partial}{\partial m} \left( 12.45 \ e^{11.18 \cdot 12.45 \ m} \right) \quad (A.21)
\]

This gives:

\[
\frac{\partial}{\partial m} \left( \frac{\partial}{\partial m} L \right) = -155 \ e^{11.18 \cdot 12.45 \ m} \quad (A.22)
\]

and at \( m = 0.2 \):

\[
\frac{\partial}{\partial m} \left( \frac{\partial}{\partial m} L \right) = -9.21 \times 10^5 \quad (A.23)
\]

Which is the slope of the derivative of the potential energy term, \(-V\), at a moisture content of 0.2. This is shown graphically in Fig. A-2.

\[
\frac{\partial}{\partial m} \left( \frac{\partial}{\partial m} L \right) = -9.21 \times 10^5 \ \frac{J}{Kg\cdotwood} \ \frac{Kg\cdotwater^2}{(at \ m = 0.2)} \quad (A.24)
\]

The linearized function is therefore given as:

\[
\frac{\partial}{\partial m} L = S_{dhw.m} \ m \quad (A.25)
\]
Fig. A-2. Slope for d(-W)/dm curve at m = 0.2.

Slope is 
\[-921000 \text{ J-Kg-wood/(Kg-water)}^2\]

at m = 0.2
$S_{dhw,m}$ is the slope of the linearized differential heat of wetting curve at moisture content $m$. In this case:

$$S_{dhw,2} = -9.21 \times 10^5 \frac{J \text{ Kg-wood}}{\text{Kg-water}^2}$$  \hspace{1cm} (A.26)

which is at $m = 0.2$.

Finally, the system differential equation is arrived at from:

$$\frac{d}{dt} \frac{\partial}{\partial m} L - \frac{\partial}{\partial m} L = 0$$  \hspace{1cm} (A.27)

This results in the following differential equation:

$$\frac{d}{dt} \left( \frac{10}{39} \frac{E h^4 \rho_{\text{wood}} s_{\text{max}}^2}{K_{\text{cond}}^2 \Delta m_{\text{max}}^2} \dot{m} \right) + \left( 9.21 \times 10^5 \frac{J \text{ Kg-wood}}{\text{Kg-water}^2} \right) m = 0$$  \hspace{1cm} (A.28)

Taking the derivative and making the symbol substitution for the slope of the differential heat of wetting, the system differential equation is given as:

$$\frac{10}{39} \frac{E h^4 \rho_{\text{wood}} s_{\text{max}}^2}{K_{\text{cond}}^2 \Delta m_{\text{max}}^2} \dot{m} - S_{dhw,m} m = 0$$  \hspace{1cm} (A.29)

Note that $S_{dhw,2}$ is the slope coefficient derived from the linearized differential heat of wetting curve at $m = 0.2$. The value of $S_{dhw,2}$ is negative for all values of $m$. When $S_{dhw,2}$ is substituted into Eq. A.29, the sign between terms of the equation will always be positive as shown in Eq. A.28.
Note that Eq. A.29 does not show a term for damping. Damping is a result of energy lost from the system as creep and acoustic emissions, but a function to describe this is not available.
Period of Oscillation Calculation

Since Eq. A.29 is in the form of a standard differential equation, the system time constant is given as follows:

\[
\tau = 2 \pi \left( \frac{10}{39} \frac{E h^4 \rho_{wood} s_{P_{max}}^2}{K_{cond}^2 \Delta m_{max}^2} \right)^{-\frac{1}{2}} - S_{dhw.2} \]  
\tag{A.30}

\[
- S_{dhw.2} = + 9.21 \times 10^5 \frac{J \text{kgwood}}{\text{Kgwater}^2} 
\tag{A.31}
\]

Inserting the appropriate values for the other constants from Table A-1 gives:

\[
\tau = 61 \text{ hours} 
\tag{A.32}
\]

This calculated period of oscillation makes use of a value for the moisture diffusion coefficient that was chosen to be 35 times that of gross wood to enable the calculated period to agree with the experimental data. This value for diffusion coefficient is reasonable for red oak.

Note that the value for \(S_{dhw.2}\) is a function of \(m\). Over the range of \(m\) from 0 to 30%, the calculated value of \(\tau\) ranges from 17 hours to 114 hours. The value of \(E\) and especially \(K_{cond}\) also vary with \(m\) and therefore affect \(\tau\). In addition, these physical properties vary with temperature and so \(\tau\) is a function of temperature. The calculated value of \(\tau\) in Eq. A.32 uses values for physical properties that correspond to the test conditions of the wood samples which resulted in the data given in Fig. 4-10 and Fig. 4-11.
Development of the Function \( k \)

The equation for elastic strain energy is expressed in terms of a constant \( k \) which describes the shape and magnitude of the mechanical load on the wood fibers resulting from the shrinkage gradient. For the system equation to be useful, this function must be expressed in terms of the water mass flow rate. The following is the strain energy equation, which gives the energy stored by the bending of wood fibers from the shrinkage gradient (from Eq. A.60):

\[
U = \frac{13}{1620} \frac{L^9 k^2}{EI} \tag{A.33}
\]

The following equation is for maximum deflection of the ends of the wood fibers as they are bent (see Eq. A.102):

\[
y_{\text{max}} = \frac{13}{180} \frac{L^6 k}{EI} \tag{A.34}
\]

Also have an equation for the mass flow rate in the wood, \( M/t \) is total mass flow rate of water from the wood:

\[
K_{\text{cond}} = \frac{M}{t} \frac{L}{A \Delta M} \tag{A.35}
\]

\[
M = \frac{\dot{M}}{t} \tag{A.36}
\]

\[
K_{\text{cond}} = \frac{L \dot{M}}{A \Delta M} \tag{A.37}
\]

It is necessary to express mass flow in terms of per kilogram of wood, since this will be a common basis for energy calculations. \( \rho_{\text{wood}} \) is density of wood:
\[ \dot{m} = \frac{\dot{M}}{V_{\text{wood}} \rho_{\text{wood}}} \]  

(A.38)

Solve Eq. A.35 for \( \dot{M} \), and use it in Eq. A.37 for \( K_{\text{cond}} \), then solve for \( \Delta m \):

\[ \Delta m = \frac{V_{\text{wood}} \rho_{\text{wood}} L}{A K_{\text{cond}}} \frac{\dot{m}}{m} \]  

(A.39)

A final equation defines the maximum deflection of fibers at the end of the sample for a given change in \( m \), given in terms of the shrinkage:

\[ y_{\text{max}} = \frac{\Delta m}{\Delta m_{\text{max}}} s_{\text{max}} h \]  

(A.40)

where:

\[ s_{\text{max}} = 0.086 \]  

(A.41)

\( s_{\text{max}} \) is the maximum possible fractional shrinkage in the tangential direction for the wood. The symbol \( h \) is half the wide dimension of the sample, or 50 mm. \( \Delta m \) is the moisture gradient along the sample which results in shrinkage. \( \Delta m_{\text{max}} \) is the maximum possible change in moisture content which is from saturated (30% \( m \)) to 0% \( m \) or a change of 30%. And \( s_{\text{max}} h \) is the maximum possible dimensional shrinkage in the tangential direction for the maximum possible change in \( m \).

\[ \Delta m_{\text{max}} = 0.3 \frac{\text{Kg-water}}{\text{Kg-wood}} \]  

(A.42)

Now solve the two independent equations for deflection to get an
expression for $k$ in terms of $\dot{m}$. The equations are repeated as follows:

$$y_{max} = \frac{-13}{180} \frac{L^6 k}{EI}$$  \hspace{1cm} (A.43)

$$y_{max} = \frac{\Delta m}{\Delta m_{max}} s_{max} h$$  \hspace{1cm} (A.44)

Combining Eq. A.42 and Eq. A.43 gives:

$$\frac{-13}{180} \frac{L^6 k}{EI} = \frac{\Delta m}{\Delta m_{max}} s_{max} h$$  \hspace{1cm} (A.45)

Substitute the function for $\Delta m$ from Eq. A.39 and solve for $k$:

$$k = - \frac{180}{13} \frac{V_{wood} \rho_{wood} E I h s_{max}}{A K_{cond} L^5 \Delta m_{max}} \dot{m}$$  \hspace{1cm} (A.46)

Substitute the following functions into Eq A.46:

$$V_{wood} = b h L$$  \hspace{1cm} (A.47)

$$A = b h$$  \hspace{1cm} (A.48)

$$I = \frac{b h^3}{12}$$  \hspace{1cm} (A.49)

The final equation for $k$:

$$k = - \frac{15}{13} \frac{\rho_{wood} E b h^4 s_{max}}{K_{cond} L^4 \Delta m_{max}} \dot{m}$$  \hspace{1cm} (A.50)
**Function for Elastic Strain Energy**

This derivation is for the elastic strain energy in a cantilever beam which is set up to simulate half of one end of the sample being dried. See Figure A3. Note that the load is given in terms of per unit length of cantilever, \( w \) (N/m). This method follows Shigley [50].

First, it is assumed that the load on the beam is parabolic, and that the beam is rigidly fixed at the left end. It is assumed that the entire beam bends in response to the load. In reality, the load varies with \( h \). Note that \( h \) is half the wide dimension of the sample. This method of modeling the strain energy is a great simplification, but gives a result that is somewhat representative of the actual situation. The assumed function for the load is given as:

\[
w = -k x^2
\]  \hspace{1cm} (A.51)

where \( k \) has units of N/m\(^3\). Summing the reactions at point A and taking counterclockwise moments as positive:

\[
0 = R_A + \int_0^L w \, dx
\]  \hspace{1cm} (A.52)

\[
R_A = \frac{1}{3} L^3 k
\]  \hspace{1cm} (A.53)

Now, sum the moments about point A taking counterclockwise moments as positive:

\[
M_{mA} = -\int_0^L x \, w \, dx
\]  \hspace{1cm} (A.54)
Fig. A-3. Loading on wood fibers.
\[ M_{mA} = \frac{1}{4} L^4 k \]  \hspace{1cm} (A.55)

Now an an expression for internal moments at some point where \( x = l \):

\[ 0 = M_{mA} - \left( \int_0^l w (l - x) \, dx \right) + M_{mRL} - R_A l \]  \hspace{1cm} (A.56)

Substitute for \( w \), integrate and solve for \( M_{mRL} \):

\[ M_{mRL} = - M_{mA} - \frac{1}{12} k l^4 + \frac{1}{3} k L^3 l \]  \hspace{1cm} (A.57)

Substitute from Eq. A.55 for \( M_{mA} \), and express for the general case in which \( l = x \):

\[ M_{mRL} = - \frac{1}{4} k L^4 - \frac{1}{12} k x^4 + \frac{1}{3} k L^3 x \]  \hspace{1cm} (A.58)

Now calculate the energy stored in the wood fibers from the bending moment. The moment varies along the length as given above. The equation for energy storage from bending, \( U \), is from Shigley [51].

\[ U = \int_0^L \frac{M_{mRL}^2 \, d\, x}{2 \, E \, I} \]  \hspace{1cm} (A.59)

Substitute for \( M_{mRL} \) from Eq. A.58 above and integrate:

\[ U = \frac{13}{1620} \frac{L^9 k^2}{E \, l} \]  \hspace{1cm} (A.60)
This is the equation for total elastic strain energy (in one half of one end of the sample) that will be used in other parts of the derivation for the system dynamic equation.

**Maximum Elastic Energy Storage**

This section models the maximum possible elastic energy that can be stored in the beam. This maximum elastic energy storage will then be compared to the maximum hygroscopic energy storage and also the energy required to evaporate water from the wood from the green condition to dry wood.

The maximum mechanical tensile stress in the tangential direction (the wide direction of the sample) that the wood can withstand before failure is given by the symbol \( \sigma_{\text{tmax}} \), and is defined as follows:

\[
\sigma_{\text{tmax}} = \frac{u_{\text{max}}}{b} \quad \text{(at } x = L) \quad \text{(A.61)}
\]

This can be restated as:

\[
u_{\text{max}} = \sigma_{\text{tmax}} b \quad \text{(at } x = L) \quad \text{(A.62)}
\]

Adapting from Eq. A.51, setting \( x = L \), and dropping the negative sign:

\[
u_{\text{max}} = k_{\text{max}} L^2 \quad \text{(A.63)}
\]

From Eq. A.63 and Eq. A.62:

\[
k_{\text{max}} = \frac{\sigma_{\text{tmax}} b}{L^2} \quad \text{(A.64)}
\]
From Eq. A.5, A.6, and A.7 and setting for the maximum elastic energy storage per Kgwood:

\[ u_{\text{max}} = \frac{13}{135} \frac{L^8 k_{\text{max}}^2}{E \rho_{\text{wood}} b^2 h^4} \]  \hspace{1cm} (A.65)

Insert the function for \( k_{\text{max}} \) from Eq. A.64:

\[ u_{\text{max}} = \frac{13}{135} \frac{L^4 \sigma_{\text{max}}^2}{E \rho_{\text{wood}} h^4} \]  \hspace{1cm} (A.66)

Now a value for \( L \) is needed. \( L \) is the length of the shrinkage gradient over which the parabolic load can be applied to result in a deflection that is equal to the maximum possible shrinkage deflection and also have a maximum allowable stress at the end. The value for maximum shrinkage deflection of the fibers is given by Eq. A.40 and Eq. A.41 with \( \Delta m \) at its maximum value:

\[ y_{\text{max}} = \frac{\Delta m}{\Delta m_{\text{max}}} s_{\text{max}} h \]  \hspace{1cm} (A.67)

\[ s_{\text{max}} = 0.086 \]  \hspace{1cm} (A.68)

\[ \Delta m = \Delta m_{\text{max}} \]  \hspace{1cm} (A.69)

Combining the above for the maximum possible \( y_{\text{max}} \) gives:

\[ y_{\text{MAX}} = s_{\text{max}} h \]  \hspace{1cm} (A.70)

In addition Eq. A.102 for deflection:

\[ y_{\text{max}} = -\frac{13}{180} \frac{L^6 k}{E l} \]  \hspace{1cm} (A.71)
This is an absolute maximum when \( k \) is at \( k_{\text{max}} \):

\[
y_{\text{MAX}} = -\frac{13}{180} \frac{L^4 b \sigma_{\text{max}}}{EI}
\]  

(A.72)

Now solve Eq. A.70 and Eq. A.72 together for the value of \( L \):

\[
L = 0.158 \text{ m}
\]  

(A.73)

When this value for \( L \) is used in Eq. A.66, the following is the maximum amount of elastic strain energy that can be stored in the given volume of wood with the assumed parabolic load:

\[
\eta_{\text{max}} = 172 \frac{\text{Joules}}{\text{Kgwood}}
\]  

(A.74)

The value for maximum hygroscopic energy storage is from Eq. A.12 with \( m = 0 \):

\[
W_{\text{max}} = 71700 \frac{\text{Joules}}{\text{Kgwood}}
\]  

(A.75)

The ratio of \( W_{\text{max}} \) to \( \eta_{\text{max}} \) is:

\[
\frac{W_{\text{max}}}{\eta_{\text{max}}} = 420
\]  

(A.76)

The energy to evaporate all the water in the wood from an initial moisture content of 80% can be calculated. The mass of water is:

\[
M_{\text{emax}} = m_{\text{max}} V_{\text{wood}} \rho_{\text{wood}}
\]  

(A.77)
\[ M_{\text{emax}} = 0.158 \text{ Kgwater} \quad \text{(A.78)} \]

And the maximum drying energy is:

\[ Q_{\text{fgmax}} = M_e h_{fg} \quad \text{(A.79)} \]

\[ Q_{\text{fgmax}} = 1.9 \times 10^6 \frac{\text{Joules}}{\text{Kgwood}} \quad \text{(A.80)} \]

The ratio of this maximum heat of vaporization to maximum elastic strain energy is:

\[ \frac{Q_{\text{fgmax}}}{M_{\text{max}}} = 11,000 \quad \text{(A.81)} \]

This is one reason the wood is so difficult to dry without fractures; about 11,000 times the maximum energy that can be stored in the wood as elastic strain energy must be put into the wood to evaporate all the water (for the assumed parabolic loading). From the standpoint of energy, the amount that is stored as elastic strain energy is negligible compared to the energy required to evaporate the water. However, it is this small amount of elastic energy in the wood that must be controlled to avoid checking damage during drying.
**Function for Maximum Deflection**

To complete the derivation for the system differential equation, an expression is needed for the deflection of the wood fibers. The same assumptions for geometry and load as were used for the elastic energy calculation are used here.

The load is given as:

\[ w = - k x^2 \]  \hspace{1cm} (A.82)

The following is from basic principals of mechanics,

\[ \frac{d^4 y}{dx^4} = \frac{w}{EI} \]  \hspace{1cm} (A.83)

Substituting for \( w \) from above:

\[ \frac{d^4 y}{dx^4} = - \frac{k x^2}{EI} \]  \hspace{1cm} (A.84)

The expression for the Shear, \( S \), in the beam:

\[ \frac{S}{EI} = \int \frac{d^4 y}{dx^4} \, dx \]  \hspace{1cm} (A.85)

\[ \frac{S}{EI} = - \frac{1}{3} \frac{k x^3}{EI} + c_1 \]  \hspace{1cm} (A.86)

Now the expression for bending moment, \( M_m \):

\[ \frac{M_m}{EI} = \int \frac{S}{EI} \, dx \]  \hspace{1cm} (A.87)
\[
\frac{M_m}{EI} = - \frac{1}{12} \frac{k x^4}{EI} + c_1 x + c_2 \tag{A.88}
\]

Now, the angle of deflection in the beam:

\[
\theta = \int \frac{M_m}{EI} \, dx \tag{A.89}
\]

\[
\theta = - \frac{1}{60} \frac{k x^5}{EI} + \frac{1}{2} c_1 x^2 + c_2 x + c_3 \tag{A.90}
\]

Now, the expression for deflection:

\[
y = \int \theta \, dx \tag{A.91}
\]

\[
y = - \frac{1}{360} \frac{k x^6}{EI} + \frac{1}{6} c_1 x^3 + \frac{1}{2} c_2 x^2 + c_3 x + c_4 \tag{A.92}
\]

Now use boundary conditions to evaluate the constants of integration. At \( x = 0 \) the following conditions apply:

\[
x = 0 \tag{A.93}
\]

\[
S = \frac{1}{3} L^3 k \tag{A.94}
\]

\[
M_m = - \frac{1}{4} L^4 k \tag{A.95}
\]

\[
\theta = 0 \tag{A.96}
\]

\[
y = 0 \tag{A.97}
\]

Substituting into the above equations, it is found that:
\[ c_1 = \frac{1}{3} \frac{L^3 k}{EI} \quad (A.98) \]
\[ c_2 = -\frac{1}{4} \frac{L^4 k}{EI} \quad (A.99) \]
\[ c_3 = c_4 = 0 \quad (A.100) \]

Substituting, the expression for \( y \) is:
\[ y = -\frac{1}{360} \frac{k x^8}{EI} + \frac{1}{18} \frac{L^3 k x^3}{EI} - \frac{1}{8} \frac{L^4 k x^2}{EI} \quad (A.101) \]

Finally, the maximum deflection at \( x = L \) and \( y = y_{\text{max}} \):
\[ y_{\text{max}} = -\frac{13}{180} \frac{L^6 k}{EI} \quad (A.102) \]
APPENDIX B, CIRCUITRY
Circuitry
The Pre-Amp for Channel 1 was followed by circuitry, shown in Figure B-1, which provided the comparator function to convert the analog waveform of the AE events to a TTL compatible digital signal that the computer could log and use as the basis for control of the drying conditions. The signal from the Pre-Amp for Channel 1 is first processed by IC3. Since all necessary amplification for this signal is provided by a 40 dB Pre-Amp gain and an additional 60 dB of gain in the AET 206, no additional gain is provided by IC3. However, in order to eliminate all DC offset that might be carried by the signal, capacitor C1 provided AC coupling. Also, C1 and R1 provide some additional high pass filtering. The voltage reference for the comparator is provided by IC1 and IC2 with associated components. After considerable experimentation the voltage reference was chosen to be 0.574 volts which is equivalent to 5.74 µV at the transducer output. Since the count rate is extremely sensitive to the comparator reference voltage, components for the reference were chosen to limit voltage drift to about 1 mV at the comparator.

The most critical portion of the circuit is the comparator, IC4 and associated components. The Burr-Brown BB3551J was chosen for its high slew rate and low offset voltage drift. These characteristics are essential for repeatable detection of the AE events. Since the output of IC4 swings between -15V and +15V, diodes D1 and D2 are used to clamp the voltage between 0V and +5V for digital TTL compatibility. IC5 provides a divide-by-10 function which was necessary to keep the rate of counts low enough for the interface chip to the computer to avoid missing any counts. The software compensates by multiplying the logged count rate by a factor of 10.

An additional function provided by the Channel 1 circuitry is the
Fig. B-1. Channel 1 comparator circuit with audio indicator.
audio indicator. Since the computer logged a number for the count rate only at 10 minute intervals, it was desirable to give a continuous indicator for the instantaneous rate of emissions. This was provided by an audio oscillator, a gate to allow the pulses through to a speaker driver, and a pulse generator to determine how long the sound would last for each event. A stream of square wave pulses at the audible frequency of 5 KHz is provided by IC7, a 555 oscillator. Each time an AE event is detected, IC6 generates a "one-shot" pulse that is long enough in duration so that IC8 can gate about five of the 5 KHz pulses through to transistor T1 and thus drive the speaker. It was found that about 5 pulses on the speaker at 5 KHz were sufficient to generate an audible "click". For mild drying conditions, the rate of audible clicks averaged about one per second. For severe drying conditions, as when the drying chamber door was opened, the clicks were so close together that the sound was virtually continuous. The audio indicator for AE could be useful to a kiln operator, for it could provide an early warning of drying problems without the need for the operator to continually monitor instrument displays.

Circuitry for Channel 2, which is similar to that for Channel 1, is shown in Figure B-2. It uses the same voltage reference as Channel 1 but does not provide an audible indicator. The primary difference for this circuit is that it provides some additional amplification. The Pre-Amp for Channel 2 provides a gain of 60 dB, so an additional gain of 40 dB is required to match that of Channel 1. The additional gain is provided by IC9 and IC10. A gain adjustment is provided by R17 so that the two channels could be matched.

The interface to the computer is through Rockwell 6522 Versatile Interface Adaptor chips. These programmable devices provide 16 digital I/O lines as well as a sixteen bit counter. This counter was
Fig. B-2. Channel 2 comparator circuit.
used to log the acoustic emissions data independent of the main computer processor. Since the maximum count of the device is about 65000, it was necessary for the computer to log data from the device about every ten minutes to avoid overflowing the counter. It was found through much experimentation that the most appropriate time period for the computer to average the count rate for control purposes was about two hours. So, one of the program functions was to read the R6522 every 10 minutes and average the count rate over a two hour period. A reasonable count rate was an average of about 1000 counts per minute. For severe drying conditions, such as that resulting from suddenly opening the conditioning chamber door, the count rate could easily exceed 100,000 counts per minute for a short period of time.

Additional interfacing, of course, was necessary for the temperature probes and the scale. For these analog signals an interface was designed using an Analog Devices multichannel analog-to-digital converter. This converter provided for sixteen analog inputs of which only four were used. The temperature probes provided a high level signal and required little signal conditioning. The scale, on the other hand, was of the bridge strain gage type and required an instrumentation amplifier with a gain of about 1000. An Intersil 7660 CAZ amp was used because of its extremely low offset and drift characteristics. The scale proved to be of little usefulness, however, because it could not stand up well to the high humidities that were encountered in the kiln.

Additional interfacing was necessary between the computer and the environmental chamber controls. The chamber used was an old one and the original controls were not adequate for the precision that was needed. So, the old controls which used bi-metallic temperature
sensors and mechanical relays for controlling the dry bulb heaters and refrigeration were redesigned. The chamber was equipped with electronic temperature sensors and solid state relays that were under the control of the computer. A software algorithm was implemented that incorporated a PID (Proportional Integral Derivative) algorithm to give better control over the drying conditions in the chamber. The final result was a system with the ability to control the dry bulb temperature to about +/- 0.1 C and the relative humidity to about +/- 0.5 %. These conditions were more than stable enough to result in a stable rate of acoustic emissions for the various aspects of the study.
APPENDIX C, PROGRAM LISTING
Program Listing

10 POKE 30731,224 'SET UP FOR 60 HZ TIME BASE
20 POKE 30724,148
30 POKE 30725,32

----------
'INPUT INITIAL CONTROLLER SETPOINTS FROM KEYBOARD

40 INPUT "DEW POINT SET, C"; DP
'INPUT DEW POINT SETPOINT
50 INPUT "DRY BULB SET, C"; DB
'INPUT DRY BULB SETPOINT
60 INPUT "CHECK RATE SET, CPM"; CS
'INPUT COUNT RATE SETPOINT

----------
'SETUP R6522 INTERFACE PORTS FOR COUNTING AE

70 POKE 40962,0 'PORT B = INPUT
80 POKE 40963,240 'LOWER 4 BITS PORT A = INPUT
90 POKE 40961,128 'RESET TTL COUNTER
100 POKE 40961,64 'BEGIN COUNTING (TTL)
110 POKE 40971,32 'SET TIMER 2 TO COUNT PULSES
120 POKE 40968,255 'SET T2 LOW LATCH
130 POKE 40969,255 'SET T2 HIGH LATCH, BEGIN COUNTING

----------
'SETUP R6522 TO COUNT 60HZ POWER FOR TIME BASE

140 POKE 32770,191 'PORT 2B BIT 6 IS INPUT,
OTHERS ARE OUTPUTS
150 POKE 32771,255 'PORT A IS AN OUTPUT
160 POKE 32779,32 'SET ACR TO PULSE COUNT MODE
170 POKE 32769,2 'HOT GAS BYPASS ON TO EQUALIZE COMPRESSOR
180 PRINT "" " 'POWER-UP MESSAGE
190 PRINT """"POWER-UP!"
200 PRINT "" "

210 PRINT DP;DB;CS 'DISPLAY SETPOINTS
220 FOR A = 1 TO 40000 'DELAY TO EQUALIZE REFRIGERATION
230 NEXT A

231 DIM C(30) 'SET UP COUNT RATE ARRAY FOR INTEGRAL TERM OF PID CONTROLLER
232 FOR I = 0 TO 30 'AVERAGE COUNTS FOR 30 TIME PERIODS
233 C(I) = CS
234 NEXT I
235 CT = CS * 30 'INITIAL TOTAL WILL BE 30 TIMES SETPOINT

240 Q = 12 'PRINT AVERAGE COUNT EVERY 2 HOURS (12 TEN MINUTE CYCLES)
250 Q1 = 0
260 Q2 = 0

'BEGIN TIMED CYCLE OF TWO HOURS

270 POKE 32776,100 'SET T2 LOW LATCH

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280 POKE 32777,139 'SET T2 HIGH LATCH, BEGIN
290 GOSUB 590 'GET TEMP AND HUMIDITY

300 D1 = DB - T0
310 BC = BC + 0.2 * D1 + 6 * (D1 - D2)
320 D2 = D1
330 IF BC < 15 GOTO 350

340 BC = 15
350 IF BC > 0 GOTO 370

360 BC = 0
370 B0 = INT (BC)
380 B0 = B0 * 16
390 IF T2 < DP THEN B1 = 2

'IF DEW POINT TEMP LESS THAN
SET POINT, TURN ON HEATER

400 IF T2 >= DP THEN B1 = 0
410 CB = B0 + B1 'COMBINE ABOVE TO GET

CONTROL WORD
420 POKE 32769,CB 'OUTPUT CONTROL WORD, BIT 0

= DRY BULB HEAT
430 T= PEEK (32781) 'READ INTERRUPT FLAG

REGISTER
440 T = T AND 32 'TEST BIT 5 OF IRF FOR

COUNTER = 0
450 IF T = 0 THEN 290 'IF TIME NOT UP, REPEAT

460 GOSUB 1050 'LOG COUNTS

470 Q1 = Q1 + C1
480 Q2 = Q2 + C2
490 Q = Q - 1
500 IF Q <= 0 THEN 520

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Program Listing

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510  GOTO 270  'REPEAT TIMED CYCLE
520  Q1% = Q1 / 12  'CALCULATE AVERAGE COUNT
530  Q2% = Q2 / 12

'PRINT DATA
540  PRINT! Q1%; "C/M", Q2%; "C/M"
550  PRINT! TO; "C", H; "%RH"
560  PRINT! W$; "KG"
570  PRINT! " "
580  GOTO 240

----------------------------------  'SUBROUTINE FOR A/D
590  V0 = 0
600  V1 = 0
610  V2 = 0
620  V3 = 0
630  FOR N = 0 TO 9  'GET AVERAGE OF 10 VOLTAGE READINGS
640  FOR I = 0 TO 3  'GET ANALOG VOLTAGES FOR 4 CHANNELS
650  POKE 32768, I  'SELECT CHANNEL
660  POKE 36864, 0  'BEGIN CONVERSION
670  H(I) = PEEK (36864)  'GET HIGH BYTE
680  L(I) = PEEK (36865)  'GET LOW BYTE
690  V(I) = H(I) * 16 + L(I)/16  'CONVERT TO 12 BITS
700  NEXT I  'READ NEXT CHANNEL
710  V0 = V0 + V(0)  'GET SUM OF 10 READINGS
720  V1 = V1 + V(1)
730  V2 = V2 + V(2)
740  V3 = V3 + V(3)
750  NEXT N  'REPEAT LOOP TO READ
760  V0 = V0 / 10  'GET AVERAGE OF 10 READINGS
770  V1 = V1 / 10
780  V2 = V2 / 10
790  V3 = V3 / 10

'CALCULATE TEMPERATURES FROM CALIBRATION CURVES
800  T(0) = 0.0417836 * V0 - 41.593
810  T(1) = 0.0415338 * V1 - 41.091
820  T(2) = 0.0416234 * V2 - 39.828
830  W = 0.01399 * V3 - 2.63

'CALCULATE WEIGHT OF LOAD
840  T0 = INT (T(0)*100)/100

'FORMAT READINGS FOR DISPLAY
850  T1 = INT (T(1) * 100) / 100
860  T2 = INT (T(2) * 100) / 100
870  T0 = INT (T(2) * 10) / 10
880  WS = STR$ (W)
890  WS = LEF$T$ (WS,7)
900  PRINT T0;T1;TW

'DISPLAY TEMPERATURES
910  FOR A = 1 TO 500
920  NEXT A

'CALCULATE HUMIDITY FROM FORMULA USING WET & DRY BULB TEMPERATURES
930  H1 = (EXP(2.30259 * 8.94)) *
     EXP (2.30259 * (-2260/ (T1+273.1))))
940  H2 = 0.000660 * 760 * (T0 - T1) *
     (1+ 0.00115 * T1)
950  H3 = (EXP (2.30259 * 8.94)) *
     (EXP (2.30259 * (-2260/(T0+273.1))))
960 H = 100 * (H1 - H2) / H3
970 H = INT ( H * 10) / 10

980 PRINT T0;"C",H;"%RH" 'DISPLAY DATA
990 FOR A = 1 TO 500
1000 NEXT A
1010 PRINT C1;"C/M",C2;"C/M"
1020 FOR A = 1 TO 10
1030 NEXT A
1040 RETURN

_________________________ 'SUBROUTINE FOR LOGGING COUNTS

1050 POKE 40961,0 'STOP COUNTING
1060 L1 = PEEK (40968) 'READ LSB FROM TIMER 2
1070 M1 = PEEK (40969) 'READ MSB FROM TIMER 2
1080 C1 = 65535 - (M1 * 256 + L1) 'CALCULATE TOTAL COUNTS

1090 L2 = PEEK (30728)
1100 M2 = PEEK (30729)
1110 C2 = 65535 - (M2 * 256 + L2)
1120 DB$ = STR$ (DB)
1130 DB$ = LEFT$ (DB$,6)
1140 FOR A = 1 TO 1000
1150 NEXT A

_________________________ 'SETUP FOR COUNT RATE PID

1151 C(30) = C%
1152 CT = CT + C(30) - C(0) 'CALCULATE NEW TOTAL

1153 FOR I = 0 TO 29 'SHIFT ARRAY
1154 C(I) = C(I + 1)
1155 NEXT I

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1156 CA = CT/30 'CALCULATE NEW AVERAGE COUNT RATE
1157 E1 = CS - C(29) 'PROPORTIONAL ERROR TERM
1158 E2 = CS - CA 'INTEGRAL ERROR TERM
1159 E3 = C(28) - C(29) 'DERIVATIVE ERROR TERM
1160 G = 0.0001 'CONTROLLER GAIN
1170 DB = DB + G * E1 + G * E2 + G * E3 'CALCULATE NEW DRY BULB SETPOINT
1180 IF DB < 75 THEN 1200 'PUT LIMITS ON DRY BULB TEMP
1190 DB = 75
1200 IF DB > DP - 1 THEN 1220
1210 DB = DP - 1
1220 POKE 40961,128 'RESET TTL COUNTER
1230 POKE 40961,64 'BEGIN COUNTING (TTL)
1240 POKE 40971,32 'SET TIMER 2 TO COUNT PULSES
1250 POKE 40968, 255 'SET TIMER 2 LOW LATCH
1260 POKE 40969, 255 'SET TIMER 2 HIGH LATCH, BEGIN COUNTING
1270 POKE 30731, 244
1280 POKE 30728,255
1290 POKE 30729,255
1300 RETURN

Notes: The above program listing format has been modified in order to make it easier to read. Deviations have been made from the standard Rockwell BASIC format. First, the indicator for program remarks ":REM" has been replaced by "'". Also the program has been renumbered from the original listing.
Vita

The author is from Carroll County, Virginia and was born on November 26, 1953. He received his B.S. degree in Mechanical Engineering with Nuclear Option in 1977 and M.S. degree in Mechanical Engineering with a Biomedical thesis in 1981; both degrees from VPI&SU. From 1979 until 1984, while completing his M.S. thesis and performing his dissertation research, he was employed as Instrument Maker Supervisor in the Department of Forest Products at VPI&SU. Here he supervised the campus electron microscope lab and fulfilled general departmental instrumentation needs. Since 1984 he has worked as Member of Technical Staff at AT&T Bell Laboratories in New Jersey. Here his responsibilities have included high frequency power conversion research, applied robotics research, fiber optic based television and telephone distribution equipment design, and design of telephone loop equipment for the European market. He is currently working in the Network Wireless Systems Business Unit of AT&T. He is a member of SME and ASME.

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