Winter 1978

MODELING AND CONTROLLING THE LUMBER DRYING PROCESS

RONALD ADRIEN LESSARD

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MODELING AND CONTROLLING

THE

LUMBER DRYING PROCESS

by

RONALD A. LESSARD

M.S., University of New Hampshire, 1970

A DISSERTATION

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In Engineering

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This thesis has been examined and approved.

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ABSTRACT

MODELING AND CONTROLLING
THE LUMBER DRYING PROCESS

by
Ronald A. Lessard

Technology is improving so much today that even difficult process control problems such as the drying of lumber will be automated in the near future. Using the prototype computer control program developed as a result of this research, an operator can define the relative importance of time, energy and final lumber quality to the computer so that the computer produces a schedule that optimizes the cost-quality trade off for available equipment and current potential lumber value. During drying, estimates of average moisture content are compared to computer predictions and if the disagreement is significant then the schedule is updated by the computer. The schedule update involves automatic adjustment of the moisture model coefficients, an estimation of present lumber condition and new optimization for the remainder of drying. Moisture transport is predicted by a finite difference approximation to diffusion. Stress is predicted by a hysteresis elastic-plastic model with stiffness a function of moisture and temperature. Model predictions of moisture content, elastic and plastic strain as well as tension failures are compared
with data taken during an operational test of the controller. Analysis of this test suggests that true optimal lumber drying control can be achieved using a computer assisted drying system.
1. INTRODUCTION

1.1 Problem Statement

Increasing consumer demand and labor costs, a scarcity of raw materials as well as a risk of catastrophic degrade losses have forced production automation into an increasingly important role in the effective management of the wood using industries. Kiln drying is one of the most time consuming and costly processes in the manufacture of wood products. Therefore, one of the most critical problems facing the industry is to develop a drying control system which would utilize conventional drying methods and minimize time, energy and loss in potential value due to drying. As a solution to this problem, the research described here is designed to develop drying models and an associated control scheme necessary to produce the basis for a responsive automatically actuated system for improving the cost effectiveness of the present lumber drying process.

The key to effective operation of such a scheme is feedback control. As a consequence, the control scheme is organized around the concept of the feedback control loop, illustrated in figure 1.1.1. The feedback loop depicts the standard industrial control as it presently exists in industry. The inner loop including the plant,
Figure 1.1.1

Feedback block diagram showing inner temperature and humidity control loop and outer schedule determination loop.
Actuator

Plant:
Kiln & lumber

Sensors:
Air temperature
Air humidity

Feedback:
Operator
Operator's manual
Company records

Sensors:
Moisture
Strain
air temperature and humidity sensors and the actuator, represent the automatic portion of the controller which determines the environmental conditions inside the kiln. The outer loop including moisture and strain sensors and the feedback element is presently the manual portion of the control, designed to determine the proper environmental conditions for drying. The operator is the most important element in this decision making loop. According to current standard procedure, he chooses the environmental conditions (humidity and temperature) based on weight measurements used to estimate average moisture content as well as personal experience, company records, short courses, technical meetings and guidance provided in the Dry Kiln Operators Manual by Rasmussen (1961). Once automated, the control can be more precise and repeatable than is possible with a human operator alone.

Some of the desired consequences of drying wood are increased strength, greater dimensional stability, improved machining and gluing performance and pressure impregnation. The objectives of drying are that the final quality defined in terms of moisture content, stress, plastic strain and extent of wood failure be within allowable limits defined by product utility. Loss of potential value due to being outside these limits (degrade loss) including time and energy required to remove water are all elements in the cost of drying. Specifically, it is desirable to minimize the cost of drying, thus producing the
best lumber at the lowest cost using available equipment.

The present standard industrial scheme for controlling moisture loss in drying is to drop the air humidity and increase the temperature in discrete steps. Water is evaporated from all wood surfaces but even though water moves more readily along the axis of the board, most water travels across the grain to the edges and wide surfaces where it is evaporated because the distance of transport is so much shorter (1 or 2 inches as compared with up to 8 feet). The time when an air humidity or temperature change (schedule step) is made is determined by the average wetness of certain sample boards taken from the load. These sample boards are periodically removed and weighed by the operator so that he may estimate the wetness.

When the estimated average wetness for the board population reaches a prescribed value, then phase 2, the quality control phase, begins. The first portion of phase 2 is called equalization. During equalization, the equilibrium moisture content conditions (EMC) are held just below the desired final moisture content value until the wettest sample board reaches the target moisture content. Equilization is a control strategy designed to reduce population variance, that is, allow slow drying boards to catch up to fast drying boards.

The second portion of the quality control phase is called conditioning. Conditioning is a strategy designed
primarily to remove differential plastic strain (permanent deformation) and associated residual stress. The proposed automatic controller will dry the lumber from the green condition until the wood reaches the quality control phase. Theoretically, such a controller can also be used for phase 2 drying but presently this portion of the drying process is of short duration and is monitored closely so that a high degree of accuracy in the computer models is required before an automatic control can be competitive. The most desired control objective for moisture content is that the entire board be in moisture equilibrium with the intended utilization environment so that minimal subsequent size change occurs.

Differential plastic strain and the resulting residual stress existing at the end of drying are especially important to quality determination when additional matching is required as in furniture manufacturing. When boards containing residual stress are cut the stresses are relieved causing the cut stock to distort. The final differential plastic strain determines the amount of residual stress. The magnitude of differential strain and residual stress are determined by the time history of drying. At the onset of drying, as illustrated in figure 1.1.2A, the outside surface of the board (shell) shrinks producing shell tension and core compression. When sustained for a sufficient time these stresses cause plastic strain in the shell and in the core. As drying
Figure 1.1.2

Stress distribution in the cross section of a drying board according to the shell-core concept
proceeds and the core begins to shrink, these plastic strains cause the stress distribution to reverse as shown in figure 1.1.2B. This stress reversal occurs because plastic deformation has stretched the shell and compressed the core so that their final dimensions do not match at equivalent moisture contents.

During the conditioning portion of the quality control phase the control strategy is to cause a plastic shell strain of the opposite sense so that the equilibrium size of the shell is geometrically compatible with the core size. The operator causes the plastic strain by adding humidity to the air. This moisture is absorbed by the shell causing it to swell forcing an even greater compression than that produced by the shrinking core. When this occurs and the added surface moisture content returns to equilibrium the drying or seasoning process is complete.

By far, the greatest loss of potential lumber quality is due to distortion and failure. Distortion may be controlled by mechanical restraint or indirectly by the drying schedule. In drying softwoods, high temperature schedules are used to cause increased plastic flow so that the material will retain the restrained shape when removed from the pile. In some hardwoods, these same high temperatures would result in failure rendering the wood unacceptable for furniture applications. Distortion may be removed by planing the surfaces
but failure generally leaves the wood unacceptable for most uses. Collapse is a form of failure due to compression of the core. Failure due to core tensile stress is called honeycombing and failure due to shell tensile stress is called surface checking. There is no explicit procedure the kiln operator can use to undo failure. The only control alternative available is to prevent failure by controlling the moisture and temperature so that stress and strain are contained within allowable limits. The danger of surface checking and excessive plastic strain is greatest during the period preceding stress reversal (figure 1.1.2B). Therefore, the schedule is not accelerated until after stress reversal. For operator convenience, trial drying schedules utilize a minimum number of step changes in environmental humidity and temperature to achieve control of drying. Since large stresses develop shortly after each step change, the changes must be accomplished after the danger of failure has passed. With any drying strategy a smooth temperature and humidity schedule can be used, accelerated drying may be accomplished sooner with no increase in failure. A digital computer can be programmed to automatically measure lumber drying and accelerate the schedule accordingly. A computer program designed to generate such a smooth schedule is a result of this research.

A control system with quality as the only objective would be straightforward but the problem is complicated
by time and energy expenditures. Time is important because costs prorated over drying time (for example; electricity to drive the air circulation fans, taxes, and wages) must be included in the cost of drying. The cost of heat energy is becoming an increasingly important variable element of drying costs. The interrelationship of all the costs is so complex that an unaided human operator cannot effectively control drying with the objective of minimizing the total drying cost. However, if the process can be modeled, then a computer can be programmed to perform the control functions.

The technology is already available to retrofit existing kilns with a simple microprocessor controller to automatically implement a smoothed version of the present industrial control strategy.

Therefore it is the objective of this research to develop an automatic scheme which realizes the drying objective of optimizing the cost-quality trade off. This requires development of mathematical predictor models for moisture transport and stress development in the lumber. An economic model which includes the cost factors involved in the drying process is also required. Finally a computer algorithm is required to realize the optimization of the cost-quality trade off.
1.2 The History of Lumber Drying Control

As described by Sloane (1965), the history of controlled lumber drying in this country began in colonial times. In the beginning, the primary concern was control of distortion in boards caused by drying. One wide face of the board was in contact with wet grass and the other exposed toward the sun and periodically flipped over in such a way as to prevent cupping distortion (concavity) due to drying. If this drying method was not entirely successful then hot water and weights were used to flatten the board out. No explicit procedure was used for preventing tension failures during drying (i.e. shakes or checks) because material was plentiful and lumber with excessive failures simply was discarded. Later when the intended use required better quality, lumber was carefully piled so as to allow for uniform circulation over all surfaces and prevent direct exposure of most boards to the sun's radiation. If the pile were partially sheltered, the maximum airflow rate could be limited so as to prevent the surface from drying too rapidly. Much later as product requirements and application techniques became more sophisticated, the need to control temperature and later humidity to assure dimensional stability was recognized. As drying technology evolved, the partial
shelter became a lumber drying kiln, a tight enclosure with both heat and humidity provided to which later air circulation was added. Finally, control systems which automatically maintained preset conditions were developed.

A review of the historical development of the feedback concept in kiln drying can be represented by a diagram (figure 1.2.1). A discussion of the kiln plant element follows in section 1.2.1. Section 1.2.2 provides information on the actuator element. The history of sensor element development is treated in section 1.2.3. The most involved element, feedback, is considered in section 1.2.4. The feedback or decision making element of the present industrial lumber drying scheme relies heavily upon the experience of the operator to qualitatively predict the consequences of a particular drying schedule strategy. However the development of mathematical models discussed in section 1.2.4 to quantitatively predict moisture and stress is necessary prior to automation of the control.

1.2.1 Kiln Plant

Developments in the kiln plant have progressed rapidly from the early versions where an open pit fire was the source of heat and natural draft (convection) the method of air circulation. When the need for humidity control was recognized, steam or spray lines were introduced into the kiln plant. Some of the latest
Figure 1.2.1

Lumber Drying Control Historical Developments
Actuator:
- Vents
- Set point control
- Time cam

Kiln plant:
- Open pit flame
- Natural draft circulation
- Steam heat
- Microwave heat
- Dehumidifier
- Solar heat

Feed back:
- Estimator models
- Kiln schedule
- Predictor models

Sensors:
- Moisture:
  - Band saw & scale
  - Load cell
  - Electrical sensors
- Strain:
  - Electrical gage
  - Photo elastic
  - Moiré grids

Kiln plant:
- Open pit flame
- Natural draft circulation
- Steam heat
- Microwave heat
- Dehumidifier
- Solar heat
research on this aspect of the drying process has involved use of microwave energy to generate the heat. As demonstrated by Barnes, Admiraal, Pike and Mathur (1976), because of the cost of energy, microwave drying is only economical for high valued hardwoods with low initial moisture concentration. Recently economic pressure caused by increasing energy costs has been at least partly responsible for the development of kilns that use the sun as the energy source.

Another solution to the present kiln plant is to simply place an air dehumidifier in an enclosed space with the lumber. This approach, currently used for low volume drying, is now being tested in higher volume application.

1.2.2 Actuator Design

The earliest form of temperature actuator or controller design probably consisted of manual vent settings and fuel control devices (valves) for the heat source. The first true controller, the set point controller, made use of pneumatic valves or electrical relays to turn the heat and humidity on or off when the sensors detect air conditions that are outside control limits. This type of set point controller is currently the device most widely used in conventional drying systems. The operator changes the setting in accordance with a pre-determined schedule and in response to sample board moisture contents. In drying softwoods, a simple time sched-
ule is often used without depending on mid-course moisture feedback. For these situations, the set point changes may be made automatically and smoothly with a commercially available clockdriven cam system.

In hardwood drying, schedule changes more often depend on the average wetness of sample boards taken to represent moisture variation in the load. A device is available which allows these changes to be automatic and smooth. The changing weight of a lumber package representative of the load is sensed by a load cell and feedback to the controller for changing air temperature and humidity. Although this approach is still in the applied research stage, it has been tested originally by Wengert (1971) and reported by Holmes and Arganbright (1976) and is currently undergoing further testing by Rice (1978). The Hildebrand Machine Company (1977) markets a control system based on sensing the thickness moisture gradient in selected boards. The gradient by this definition is the ratio of core wetness measured by electrical resistance sensors inserted in sample boards to the electrical resistance of a cellulose material maintained at equilibrium moisture conditions by the circulating kiln air.

1.2.3 Sensors

The earliest wetness sensing scheme and the scheme
predominantly used today consists of a saw to cut samples, a scale to weigh them before and after drying and an oven to dry the samples. Even the idea of a load cell to sense the weight of a large sample of the load and thus its moisture loss still requires an initial moisture sample using the oven-dry method. The Hildebrand (1977) humidity sensing scheme (the electrical resistance of a blotter paper consistency cellulose element), is a remote sensing version of the technique of weighing thin endgrain samples of wood to sense equilibrium moisture content (EMC). The core moisture sensor in the Hildebrand System measures the electrical resistance of the wood to infer wetness. The Delmhorst Instrument Company (1977) a pioneer in electrical moisture sensing has marketed a sensing system which infers the moisture gradient in sample boards from electrical resistance of electrodes placed in both the shell and the core. Couture and Hill (1974) have reported on basic research toward an improved point sensing technique using a wood element resistance sensor inserted into a drilled hole in the sample board.

Moisture sensing alone may give enough information for industrial lumber drying control but for mathematical model development, a measurement of drying strain is also necessary. The classical approach for stress evaluation is to cut a cross sectional test sample at different times during the drying process but in the industrial environment this is most often done during the quality control
phase. The cross sectional block shown in figure 1.2.2A is cut into a fork shaped section as shown in figure 1.2.2B. The sign (+,-) of the elastic stress gradient is indicated by deflection of the prong after cutting as shown in figure 1.2.2B. If the length of the prongs are precisely measured before and after cutting then the sign of the average elastic stress in each prong is also indicated.

Estimates of stress using these strain measurements for control purposes is still only qualitative without knowledge of the stiffness properties of wood. The elastic and viscoelastic properties of red oak were measured by Youngs (1957) over the entire moisture and temperature range applicable to the present drying strategy. Red oak which dries slowly and splits easily is most often used for these studies because it is the most difficult species to dry. The University of New Hampshire drying research program has also focused on red oak because the above studies represent the most complete data set available on wood properties and lumber response to drying. Information on wood properties and slicing can be used to develop a sufficiently accurate model to estimate components of strain from total strain measurements. Ugolev, Krotov and Kuznetsova (1971) report measurement of total strain is very important since this parameter is more sensitive to changes in the kiln environment and more closely related to failure than measurement of moisture content. Research on techniques for measuring total drying strain while the board is in the kiln using
Figure 1.2.2

Block cross section sample before and after cutting prongs to determine the sign of the elastic stress gradient
strain gages, photoelastic sensors and moire grids is reported by Chiu (1973) and Sewell (1975).

1.2.4 Feedback

Feedback involves the processing of sensor information to determine the control input setting. The degree of sophistication of this translation process has been evolving since 1900. It requires estimation models to generalize information on the measurement of sample boards to provide information about the mean and variance of the lumber population (kiln charge). Models are also needed to predict future behavior of the population.

Prior to this work a complete set of quantitative estimator and predictor models did not exist. Therefore much of the research work was directed at development of these models.

The present industrial control scheme outlined in section 1.1 requires a moisture content sensing method that is both time consuming and destructive to the wood sampled. Furthermore, the sample size chosen is usually a very small fraction of the entire lumber population. To compensate for the uncertainty of estimating with such a small sample, the control during the first phase of drying is based on the average of the wettest half of the sample boards. The drying schedule is then paced by the slowest drying boards. With this strategy, i.e., using a biased estimate instead of estimating the average, the operator dries the boards
so that surface checking or honeycombing (tension failure in the core of the board) will not result. Such a strategy is designed to give the operator ample room for error but may be unnecessarily conservative for a completely automatic control. A more precise approach would involve using measurements and mathematical models to estimate the statistical distribution of the moisture content in the kiln charge.

The moisture prediction model has postdated the mean and variance estimator models. To be complete the predictor model for drying requires a coupled heat diffusion and mass transfer system. The output of the heat and wetness concentration models then drives the stress-strain model. When kiln air temperature is changed, wood temperature equilibrates within a few hours which is essentially a trivial delay when compared to the weeks it takes to dry hardwoods. Therefore, for all practical purposes, in the theoretical analysis thermal diffusion can be taken as instantaneous. Thus the whole board is modeled as being always at the kiln air temperature.

Research into the drying phenomena is too extensive to completely outline here, so only the highlights will be presented. Two contrasting ideas that often emerge are that moisture transport is driven by the moisture concentration gradient or by the vapor pressure gradient. Rosen (1976) defends the concentration gradient position while Bramhall (1976) believes the vapor pressure gradient
is the real driving force. As pointed out by Skaar (1977), neither is entirely correct as both mechanisms contribute to moisture transport in a significant way. Neither the concentration gradient nor the vapor pressure gradient models have been presented as being effective predictors above the fiber saturation point. Wengert (1976) tested the vapor pressure driven diffusion model below the fiber saturation point and achieved reasonably good results. Couture (1969) tested the concentration gradient diffusion model above fiber saturation with qualified success and concluded that a polynomial form for the diffusion coefficient would be most appropriate. For purposes of modeling, the same general mathematical form of the equation is used to describe both mechanisms of moisture transport. The difference in driving force is accounted for by the functional dependence of the diffusion coefficient on moisture and temperature which is discussed by Wengert (1976).

For feedback control purposes, the present techniques for measuring strain distribution through the thickness of drying lumber (prong test) are more costly of operator time and as destructive as moisture sampling. Although less lumber is sampled the qualitative stress gradient information obtained is still very valuable to the kiln operator. The connection between stress and plastic deformation was recognized as early as 1917 by Tieman (1917). Shortly thereafter, the prong test was developed to detect the stress gradient. Conservative schedules, which were the first organized dry-
ing strategy of the time, resulted from this general know-
ledge of drying stresses. Thus a quality control strategy
was developed using the prong test (figure 1.2.2) as a de-
tector of the desired null stress gradient at the conclusion
of drying. A go, no-go detector is a primitive form of
estimator which in the case of the prong test is still used
in today's industrial control scheme. By 1940 Peck (1940)
was using a slicing technique to establish the point of
stress reversal as a hinge point in the drying process
(figure 2.2.3.12). It became clear from these studies that
drastic relative humidity changes could be made to acceler-
ate drying in the post stress reversal period without fear
of surface checking. This represents a significant step in
the evolution of kiln drying strategy. Torgeson (1951)
published a completely new series of stress related kiln
schedules which are the basis for the schedules used today.
At the present time, however, there is no quantitative
stress estimator used explicitly in the control of lumber
drying. Design of an efficient and accurate stress estima-
tor is a very difficult thing to accomplish. The best
analysis was done by Youngs and Bendtsen (1964) using a two
dimensional model.

If it is granted that stress estimates are difficult
to obtain then stress prediction presents even greater prob-
lems. For example, red oak shrinks twice as much in the
direction tangential to the rings as compared to the radial
direction. Given the cylindrical form of the log this is
a difficult behavior to model. However, it is further complicated by the oblong boundary conditions imposed by the sawn board. The first qualitative models tended to emphasize the oblong board symmetry as being the most important and thus adopted the shell-core model for analyzing drying stress development. Quantitative models simplify this two dimensional phenomenon to a one dimensional model. The board is visualized as long interacting wood strips in concept similar to the slices depicted in figure 2.2.3.12 transferring stress only to the interaction boundary. Ugolev (1959) used a simple spring to define the stress-strain relationship for each strip. Meric (1974) advanced this idea further by using a Maxwell series spring-dashpot model to predict wood stress-strain behavior for the interacting strips. Sinyak (1975) modeled the slice elements as springs but increased the spring stiffness of all the springs after a specified drying time. This had the effect of causing the simulated elements to exhibit plastic strain memory and thus cause the model to predict stress reversal. Only Meric compared his prediction to McMillen's (1955) data and then only with qualified success. Since his initial elastic model study, Ugolev (1976) has tested a finite element model and is in the process of using it to develop an improved drying stress control strategy.

Models alone are not sufficient to define the information processing feedback function. Drying objectives must be chosen and, using the predictor models, a control strat-
gy developed to reach these objectives. Drying objectives implied by the most widely used moisture content schedules are time (duration) and final quality. These schedules are designed to keep drying stresses within safe limits yet dry the lumber as quickly as possible. Because wood is more pliable when hot and wet, high temperature (100°C) schedules may be more appropriate for some situations. Rather than limiting stress, the strain limit is extended by the high temperature and the material deforms without breaking. Therefore, high temperature implies a different strategy. Heat is used to alter the mechanical properties of the lumber. The results of this strategy are reviewed by Lowry, Krier and Hann (1968). The high temperature strategy works best in drying softwoods because the moisture leaves the board rapidly enough to prevent the steep shrinkage gradients associated with failure. For some softwoods this strategy has met with success but for hardwoods such as red oak the moisture transport rate is low and high temperature drying has resulted in considerable mechanical failure.

Another strategy being introduced in industrial drying operations is called Continuously Rising Temperature (CRT). The objective of the CRT scheme is to maintain a constant transfer of thermal energy into the lumber. As a consequence, the rate of drying is also constant throughout the drying cycle. Thus, the minimum time objective is addressed directly but final quality is considered only indirectly. The constant drying rate most appropriate for
a species, as determined by trial and error, should be slow enough to prevent mechanical failures. Results of this strategy when applied to drying eastern hemlock are reported by Noffsinger (1976). The strategy is simple to automate but inappropriate for many situations because mechanical quality is only a secondary objective. For example, with hardwood drying, good mechanical quality is more important than a short drying time. For this reason a strategy based on stress and strain control such as being developed by Ugolev (1976) and as discussed in this dissertation has the greatest chance for success.

Summary

The literature review established certain points of departure for research aimed at developing an automatic wood drying control scheme which is outlined below. Since there is clearly no best sensing scheme for moisture content and strain, the feedback element of the controller must by design be independent of the sensing devices used. Presently only average moisture content can be economically estimated, therefore, it is the only measured output which can be required by the controller for feedback purposes. The average of the wettest half of the boards has been traditionally used for feedback so that drying is paced by the most slowly drying boards in an attempt to get zero-defect lumber. However an optimum solution does not necessarily produce a zero-defect result. In order to determine
an optimum solution an unbiased mean estimator and predictor model must be used with the variability in the population being accounted for by a separate model.

The available models for predicting mean moisture content that require only the initial moisture content do not predict accurately enough for control. Inaccuracy in the prediction can, however, be periodically reduced by using measured average moisture content to correct the prediction and thus the diffusion coefficient. This correction procedure can allow the designer to use a simpler more computationally efficient model.

Since the stress estimator technique of Youngs and Bendtsen (1964) requires measurements impractical for an industrial environment and the prong test does not provide all the information needed, the stress estimate must be independent of such measurements and determined solely by the drying model. The finite element stress-strain model used by Ugolev (1976) would require too much computer time to be practical for a schedule optimization search. Therefore a one dimensional model combining the elastic, plastic and viscoelastic elements of the stress-strain relationship is the only alternative. Such a model can utilize Youngs (1957) work on red oak to incorporate into the model the effect of moisture and temperature on stiffness.

Present drying strategies such as CRT (see Noffsinger (1976)) are designed to control the rate of drying to minimize the drying costs related to time and to avoid
costs due to loss in potential lumber value caused by mechanical degradation. With adequate models and an efficient computer optimization scheme, however, it is possible to state all the drying costs explicitly. For this reason the kiln strategy for this research is a drying schedule that will minimize the total drying cost.
1.3 Kiln Control Scheme

The drying process is the most time consuming and energy demanding phase of wood products production. Furthermore, present drying strategies are all suboptimal and most are manually implemented. A completely automatic optimal lumber drying controller could provide improvements in wood drying which consume less time and energy and result in less degrade. The optimal controller designer must understand the relationship of the lumber drying response to the control variables of air temperature, humidity and velocity. He must also understand that there are control noise limitations to attaining the desired control variable values. In controller design this understanding is formalized as a mathematical model for the drying plant or device being controlled (see section 1.3.1) composed of the kiln plant or dry kiln (see section 1.3.2) and the lumber plant or kiln charge (see section 1.3.3).

The controller designer must further understand that the optimal system should be compatible with the existing industrial kiln drying scheme so that equipment currently in operation can be retrofit with the automatic controller. In order to accomplish this, the controller designer must formalize the present industrial
control scheme. This is not an easy task since it includes measurement procedures and their limitations as well as lumber drying facility economics as outlined in section 1.3.4.

1.3.1 Drying Plant

From examination of figure 1.1.1 it is difficult to separate the inner automatic air temperature and humidity control loop from the drying plant. The plant, the loop and the lumber sensor block are detailed in figure 1.3.1. The circle in the diagram represents a summing node. The output signal of this node is the difference between the desired air temperature and humidity represented by $U_1$ and the measured kiln conditions represented by $Y_1$. This control error signal determines whether heat and humidity are increased or decreased. The conditioned air output of the kiln plant is also the input to the lumber plant $U_2$. The air condition sensors may be placed either on the input side of the kiln charge or on the output side (represented by $Y_2$) or both. Either signal or a combination of both $U_2$ and $Y_2$ may be fed back to the summing node. The inner control loop is completed by the actuator depicted in figure 1.1.1 composed of the summing node and the mechanisms which open and close vents, heaters and spray or steam valves.

Often in commercial operations the kiln charge (lumber plant) is large enough so that there is a signifi-
Figure 1.3.1

Drying plant block diagram showing breakdown into the kiln plant, the lumber plant and the inner feedback control loop.
A flowchart showing a process involving sensors in a kiln and lumber plant. The sensors measure air temperature and air humidity in the kiln, and moisture and strain in the lumber plant. The input labels are $U_1$ and $U_2$. The output labels are $Y_1$ and $Y_2$. The chart indicates a feedback loop.
cant steady state difference between the temperature and the humidity of air entering and that exiting the load. This difference is a function of the temperature and moisture content of the lumber. The standard industrial procedure to correct this uneven drying situation is to reverse the direction of airflow every few hours. The position of the board in the kiln determines the amplitude of the cycling of air temperature and humidity due to the reversal of airflow. Although the cyclic component of $U_2$ was insignificant for the experimental size kiln used in this research and therefore neglected, in large industrial operations it may contribute significantly to variation in the final quality of the lumber by causing surface checks.

1.3.2 Kiln Plant

Although many types of dry kilns are in use today, the important drying capabilities of each can be summarized in a very simple model. For example, within each kiln plant the time delay between setting new conditions on the kiln control panel and realizing those conditions in the air passing over the lumber surface may be minutes and sometimes hours. Even at the extreme, however, the delay is very short with respect to the time required to transport moisture within the board. Therefore, it is reasonable to model the change to steady state condition as instantaneous. Although the process is approximately
instantaneous and linear, there are practical limits to
the temperature and humidity conditions that can be
attained in steady state. A hard limit model as depicted
in figure 1.3.2 is needed to deal with this problem. In
the feedback path for $Y_2$ shown in figure 1.3.1 the influence of moisture being released by the lumber on the air
humidity is accounted for by adjusting the limits accordingly. For example, a kiln with limited venting capacity
may have a dry limit EMC higher than normal at the begin­ning of the cycle.

Although using the hard limit model presents no
problem for automatic schedule determination it masks a
significant operational problem. Kiln adjustment involves
not only steady state effects but also delayed effects
due to the heat and humidity stored in the lumber. Fur­
thermore, set point controllers in use today are not
designed to adjust air temperature and humidity from one
setpoint to another in a safe manner. After making a
change in setpoint, the operator must be careful that
the dry-bulb temperature does not race ahead of the wet­
bulb temperature or vice versa. Undesireable spreads in
these temperatures not anticipated in the drying strategy
may cause failure. If humidity is added by steam, as
it often is, control is difficult because the two vari­
ables are coupled. Heat is added when only humidity is
desired. This problem is compounded by the fact that the
set point calibration is usually inaccurate and has a
Figure 1.3.2

Drying plant block diagram showing hard limit approximation to the kiln plant model
significant dead zone due to wear in the control setting mechanism. For these reasons, readjustment of the kiln can be slow and tedious. Therefore, a large change is frequently made by a series of small step changes each coming to equilibrium before proceeding further. With advances in microprocessors the technology is now available to accomplish this adjustment procedure automatically.

1.3.3 Lumber Plant

The lumber plant is the most complex element of the entire drying control system. Heat diffusion, moisture transport and stress development are occurring simultaneously in the lumber material whose transport and mechanical properties are a function of both wetness and temperature. The temperature of the lumber adjusts to changes in the air temperature in two to four hours time. Since this time span is negligibly short with respect to the drying process, the temperature equalization time is modeled as an instantaneous phenomenon. Although thermal gradients are set up as a result of coupling between thermal diffusion and moisture diffusion, according to Kollman (1968) these gradients are small. Therefore the board temperature is always taken to be at the air temperature.

The model for the lumber plant can, therefore, be simplified to a moisture transport and stress-strain model combination. Loss of moisture results in shrinkage
and the subsequent shrinkage gradient results in a stress gradient. Although Skaar (1972) indicates shrinkage induced stress can depress the equilibrium moisture content of wood for a given humidity condition, at stress levels developing in drying, the effect is negligible and therefore, is not included in the model.

Since the drying surface is usually rough sawn, some thickness at the surface must be machined away after drying. Because the lumber plant model only needs to represent that volume of the board used by the customer as solid wood, the physical boundary for the lumber plant may be taken as indicated schematically by the dotted lines in figure 1.3.3. The wood shell, usually about 1/16 inch thick, acts as a buffer during the drying process. Fluctuations in EMC conditions around the boards produce delayed wetness changes at this lumber plant boundary. Not only is the input air humidity component of $U_2$ delayed but the response at the plant boundary is filtered or smoothed out. Instant fluctuations in surface humidity result in gradual transitions in moisture content at the plant boundary. While it is true that this outside shell exerts stress on the lumber plant, the shell is so thin, that the amount of stress transferred to the entire cross section of the lumber plant can be assumed to be negligible. The effective depth of the lumber plant boundary is determined by adjusting a particular coefficient of the moisture model. Since
Figure 1.3.3

Physical lumber plant diagram illustrating plant boundary
Boundary of lumber plant
lumber plant failure is most likely to occur first at the boundary interface, the choice of the boundary drying time constant (τ) is important to the failure estimate. The constant τ is described in section 2.2.2.

1.3.4 Control Scheme Description

Since retrofit is a consideration, the control scheme adopted in this research is designed to be as flexible as the present industrial control scheme. This scheme presently uses the average moisture content for the wettest half of the sample boards and is used along with the schedule in the Kiln Operator's Manual (Rasmussen (1961)) to determine when changes in air temperature and humidity should be made. The moisture sensing procedures now used are sufficient for operation with the optimal controller described here. Instead of using the average of the wettest half of the sample boards, the average of all the sample boards are entered into the computer. Moisture content measurements are used by the controller to check the model prediction and to refine the prediction model coefficients if necessary. Changes in kiln interior environment are determined by the computer schedule which can be updated (modified) after each measurement.

Present industrial control schemes utilize the prong test to sense strain distribution. The prong test
is used during the first portion of the drying cycle to
determine the time of stress reversal because accelera-
tion of drying cannot usually be tolerated until this
point has been passed. In this research the results of
the prong test have been used to evaluate the mechanical
model prediction but the prong test is not required for
optimal control. In its present version, the optimal
controller is not designed to refine mechanical model
coefficients based on deflection measurements, but with
some insight this can still be accomplished by adjusting
the appropriate model constants.

The second phase of the drying process is the qual-
ity control phase. Moisture sensing is used during the
equalization portion of this phase to determine when the
population moisture content variance has been reduced to
an acceptably low value. The prong test is used during
the second portion or conditioning phase to determine
when the residual stress gradient has been eliminated.
With an optimal controller, this second phase is simply
a drying situation with a new initial lumber state.
There is no reason that this phase must be done separately
although an improved model for population variance and
improved sensing techniques may be needed before the
automatic controller can be competitive with this phase
of the present control scheme.
Summary

There is no question that a smooth continuously variable schedule would be better for the lumber plant than the step change schedule used in the present industrial control scheme. Since step changes in air conditions cause large transition stresses, the step change must be delayed until the danger of failure is past which wastes drying time. A smoother schedule could be designed to accelerate the drying earlier in the drying process without the sharp increase in stress and the resultant failure. The schedule in this example is only designed as a step process for operator convenience. An automatic controller by Hildebrand (1977) is designed to follow a smooth continuously variable schedule but will only work with the Hildebrand drying system. Because the Hildebrand controller is not a retrofit solution a microprocessor control device is suggested. The microprocessor has the added advantage that it could be programmed to detect failure in the sensor system such as a dry wet-bulb sensor sock. On detecting any dangerous condition, the microprocessor can be programmed to trigger an alarm and if necessary to shut down the kiln safely until the operator arrives to correct the situation.

Even though Hildebrand manufactures a device which can produce a smooth schedule, no device exists which
can determine what the optimal smooth schedule should be. The algorithm to generate that schedule is developed in this dissertation. The schedule optimization algorithm requires mathematical descriptions of the kiln plant modeled as a hard limit and the lumber plant described by a moisture transport model (section 2.2.2) and a stress-strain model (section 2.2.3).

In addition to the more obvious advantages of control precision resulting from using the computerized system, the operator will be freed from routine decisions about schedule temperatures. He can, therefore, concentrate on improving the overall efficiency of his drying operation and regulate the final quality of the lumber more precisely to meet each customer's needs.
2. OPTIMAL CONTROLLER

2.1 Software System Overview

By using the optimal controller instead of the Kiln Operator's Manual (see Rasmussen (1961)) to determine the lumber drying air temperature and humidity, the dry kiln operator will be able to produce dry lumber of higher quality in less time. The operator will likely come to think of the controller, an elaborate computer program referred to as the software system, as a dynamic individualized schedule. Since the schedule is dynamic it can be modified at mid-drying to account for drying differences between or within a species or to account for deviation from the schedule. The schedule can also be individualized to suit the characteristics of each drying facility. This individualization occurs because the schedule is specific not only to species but also to the drying economics involved. Although it will not be obvious to the operator, the schedule produced by the program will also be optimal. That is, for each lumber drying situation, the schedule will be the single combination of energy and drying time that will produce the desired final quality at minimum cost.
2.1.1 Control Loop

The only control procedure the operator now performs which must be modified is consulting the Kiln Operator's Manual (Rasmussen (1961)) or company records to determine the schedule. The cycle of operations as depicted in figure 2.1.1 will still involve measurement of both initial and intermediate moisture contents. During the conditioning period, a measurement of the elastic strain gradient by the prong test will also still be required.

Prior to beginning the test, the operator must determine the coefficients of the economic model that define the relative importance of (1) time, (2) heat energy and (3) final quality determined by: (3a) moisture content, (3b) residual stress, (3c) plastic deformation and (3d) tension failure. The procedure for determining these coefficients is discussed in section 2.3 Economic Model.

Also prior to beginning the test, the drying model coefficients must be determined. This involves determining the moisture model coefficients and, in the present version of the controller, presetting the stress model coefficients. The moisture prediction model coefficients are optimized for the particular drying situation and may be reoptimized during the drying run (see section 2.1.2).

The operator now runs the program to determine the optimum schedule and starts the drying process by setting the air temperature and lumber EMC as prescribed by the computer generated schedule. Since the computer schedule
Figure 2.1.1
Control loop illustrating required duties of the kiln operator when using the computer controller
Optimize:
1. Schedule
2. Model

Set:
1. DB temperature
2. WB temperature
3. Air velocity

Measure:
1. Moisture content
2. Strain

Start
is continuous, a set point kiln control should be changed at least once a day to get a reasonably close approximation to the prescribed values at intermediate times. The moisture content need not necessarily be measured this often.

If for one reason or another the prescribed schedule is not followed precisely then the operator must reoptimize the schedule. If the moisture prediction disagrees with measurements and the measurements are correct, then the operator must first reoptimize the moisture prediction model before reoptimizing the schedule. The control cycle is then complete. The more often the cycle is performed, the more precise the control will be.

2.1.2 Model Optimization Loop

The model prediction of lumber response is considered optimum when the mean square error between prediction and measured response is a minimum. Finding the model coefficients which produce the minimum is an iterative process performed entirely by the computer (see figure 2.1.2). The information the operator must supply to the computer is the schedule and moisture content measurements. A trial set of drying model coefficients is used by the model to generate a trial mean square error for the prediction. To estimate the required drying coefficients, the optimization algorithm (section 2.4) will use the set of error values and trial coefficients that
Figure 2.1.2

Optimization loop illustrating the sequence of events performed by the computer during automatic adjustment of drying model coefficients
Drying coefficients

Schedule: Air temperature, air humidity

Moisture model

Measurements: Moisture content

Mean square error

Optimization algorithm
minimizes the error. The error for the estimated coefficients is calculated and the process repeats until the algorithm detects that the estimated coefficients are optimal. This best set of coefficients then determines the optimized model.

Model optimization is a key feature of the controller. By optimizing the model to measurements made during the drying process, the prediction of the drying behavior for the remainder of the test will be improved. During the controller evaluation test described in section 3.2, this improvement in the prediction is a dramatic illustration of the value of the effective use of feedback information.

The model optimization feature is not limited to simply improving prediction during a particular drying run but can be used to improve the initial prediction of successive runs. If the model is optimized at the end of each run, information will be gained on the value of the drying coefficient at all the temperature and moisture content combinations that occur in the lumber during that run. The drying coefficient equation can be used to generate a pseudo data set made up of moisture content, temperature and drying coefficient combinations. As the data set is expanded by successive runs for the same species, then the composite drying coefficient model can be determined by performing a multiple regression on this pseudo data set. In this way, the model will become more
general and hence the initial prediction will statistically improve as the operator accumulates drying experience with the controller. This phenomenon might be called a semi-adaptive scheme by control theorists but to the operator it will appear as though the controller is learning. Details of the procedure involved in accomplishing this improvement in the initial prediction will be discussed in sections 2.2.2 and A.3.

2.1.3 Schedule Optimization Loop

Schedule optimization is determining the time sequence of EMC and temperature values that will produce an optimal cost-quality trade off. This trade off is defined by the economic model shown in figure 2.1.3 and discussed in section 2.3. To determine this cost, the economic model needs predictions of: (1) lost heat energy, (2) drying time and (3) final quality as determined by: (3a) moisture content, (3b) residual stress, (3c) plastic deformation and (3d) failure from the physical models. The prediction of (1) heat loss is from the heat loss model described in section 2.2.1, (2) drying time and (3a) final moisture content are predicted by the moisture model described in section 2.2.2, (3b) residual stress, (3c) plastic deformation and (3d) failure are predicted by the stress model described in section 2.2.3. All of these predictions are the result of a trial schedule defined by the optimization algorithm. The search procedure for the optimum is identical to the pro-
Figure 2.1.3

Optimization loop illustrating the sequence of events performed by the computer during automatic determination of temperature and EMC schedules
procedure used to optimize the moisture model.

Although the form of the model is predetermined by the controller, the coefficients that determine species and thickness are set by the operator. In fact, the moisture model coefficients which determine the representative lumber species and thickness and two mechanical coefficients that specify the effective shrinkage function (discussed in section 2.2.3) must be set prior to schedule optimization. These coefficients as well as some critical output values are stored by the computer in work vectors RW (Real Work Vector) for real values of IW (Integer Work Vector) for integer values. Certain IW values are also used to determine the particular function the controller will perform. These RW and IW values are listed with explanation in the documentation section of the controller computer program listing in Appendix 6 and will be referred to by index number when encountered in the text.

Summary

All the functions of the computer controller are generalizations of the same functions performed in the present control scheme. Measurements are now recorded by the kiln operator. With the computer controller those records can be stored more compactly and be more readily accessed for reference.

Depending on his understanding of wood physics, the operator is able to predict the consequences of modi-
fying certain portions of the drying schedule. The computer models can predict the consequences of a given schedule more precisely than is possible for an operator. The predictive ability of the models can also be improved by scientists and engineers.

Using model optimization and the procedures discussed in Appendix A.3, the computer controller also has a greater potential for improvement from successive runs with the same species than conventional control methods. The most important feature of the controller, however, is that the schedule produced is optimal. By using the models to weigh drying performance of a representative set of all schedules possible, the computer controller can determine the particular schedule that best accomplishes the drying objectives according to priorities set by the operator.

The predictive models are discussed in section 2.2, the model used to convert drying performance into economic terms is discussed in section 2.3, and the optimization algorithm that automatically directs the search for the optimal schedule is discussed in section 2.4.
2.2 Predictive Models

2.2.1 Heat Loss Model

Since conservation of energy is becoming economically important and drying is the most energy consuming step in the preparation of lumber, a heat loss model must be included in the design of the optimal drying controller. A model specifically designed to calculate the heat loss during drying has been advanced by Shottafer and Shuler (1974). In Shottafer and Shuler's model, heat consumption is divided into six components. Adopting this approach the six components are incorporated into the simplified model developed for the control system.

The first component (H1) is the heat required to raise the temperature of the wood. The second component, the heat of desorption (H2), is that energy required to overcome hygroscopic forces between the water and the wood. The third component (H3) is the energy required to raise the temperature of the water that remains in the wood at the end of drying. Usually the mass of this moisture is in the range of from 6 to 10 percent of the wood's mass. The fourth component (H4) is the heat required to evaporate the water from the wood surface. This is called the latent heat of vaporization. The
fifth component (H5) is the heat required to raise the temperature of the incoming humidified air. In most lumber drying kilns, moisture being removed from the wood is vented to the outside air and is replaced by colder outside air. The total heat loss through the walls, roof and floor is the sixth component (H6). This last component depends on the construction characteristics of the walls, floor and roof including insulation thickness and type. To calculate a heat consumption estimate for a particular drying facility, the model used by Shottafer and Shuler with certain important modifications and improvements has been programmed and is available from Engaliechv (1977).

Since a disproportionate amount of computational effort is required, the schedule optimization does not use a complete heat loss model. Only four of the six components are directly affected by the choice of schedule. H1 and H3 depend on the difference between the final schedule temperature and the temperature of the air outside the kiln at the end of drying. The H5 component depends on the quantity of air vented and the temperature of the air when it is vented. The heat loss H6 through the kiln boundaries is calculated by multiplying the inside-to-outside temperature difference by a conversion coefficient and by time. Since the sum of H1 and H3 contributes less than 10% to the total heat, these components were neglected. The remaining components H5 and H6 are proportional to the inside and outside temperature difference,
therefore, the following simplified model was adopted:

\[ HC = \int_{0}^{T} K_1 (\theta - \theta_0) \, dt \quad (2.2.1.1) \]

\( HC \) = economic cost of heat energy expressed as a fraction of the potential dry value of the lumber (no units)

\( \theta \) = dry bulb temperature inside the kiln (degrees F)

\( \theta_0 \) = dry bulb temperature outside the kiln (degrees F)

\( T \) = final time (days)

\( K_1 \) = economic conversion coefficient \( \left( \frac{1}{\text{degrees days}} \right) \)

\( HC \) is calculated directly in economic terms because heat loss in BTU is not required by the controller. The procedure for determining \( K_1 \) is explained in section 2.3.

2.2.2 Moisture Transport Model

Most drying research has been directed toward developing a moisture prediction model. The lumber drying control objectives including those related to mechanical quality depend on the wood moisture content. Lumber is useless for many applications if it continues to dry after it is put into service. Thus control of final moisture content is important. Lumber cannot be used for furni-
ture if it distorts while being machined. This distor-
tion occurs if moisture gradients are not removed and if
residual stress is present. Residual stress is determined
in part by the time history of shrinkage which is in
turn determined by moisture content. Failure also depends
on the shrinkage gradient. Therefore, predicting mois-
ture content for the entire drying process is important
in most applications.

2.2.2.1 Moisture Content Description

Since boards which make up a green kiln charge come
from different locations in different trees, they all have
a different average initial moisture content. Moisture
content is defined as:

\[ M = \frac{WW - DW}{DW} \times 100 \]  

(2.2.2.1)

\[ M = \text{percent moisture content} \]

\[ WW = \text{wet weight of the sample} \]

\[ DW = \text{oven dry weight of the sample} \]

An example of how the initial average board mois-
ture content might be distributed within a charge is
shown in figure 2.2.2.1. Since the shape of the distri-
Figure 2.2.2.1

Histogram of an initial average moisture content distribution for boards in a dry kiln charge
bution is reasonably close to being normal, this popula-
tion of board moisture contents might reasonably be
characterized by its mean and variance. As the average
moisture content approaches target equilibrium, the bell
shape of the distribution curve will distort. The quickly
drying boards will be held at the equilibrium moisture
content until the more slowly drying boards catch up.
This will skew the normal bell curve shape of the distri-
bution. In fact, this catch up period, called equaliza-
tion in the present industrial control scheme, is purposely
controlled by the operator to reduce the variance of mois-
ture in the population.

Therefore, a model that predicts the population
mean and variance would be required for control purposes.
Mean population moisture content is accounted for with a
simple model but research by Fell (1978) must be extended
before a model of population variance is available. Until
then, application of the optimal controller is limited to
the pre-equalization phase of drying. When a complete
population model is available, equalization may be in-
tegrated into one continuous drying cycle. Statistics for
the four drying tests conducted in this study are presented
in Appendix A.2.

Moisture content is also variable along the long
axis of the board. Two typical examples are shown in
figure 2.2.2.2. As pointed out by Wengert (1977), there
is a steep moisture gradient within six inches of the
Figure 2.2.2.2

Plot of average cross section moisture content versus the Z coordinate of the board
Moisture content (%) vs. Z (inches)

Tangential board

Moisture content (%) vs. Z (inches)

Radial board
board ends (not plotted in figure 2.2.2.2). To lessen the effect of this gradient on end checking, splitting and distortion, the kiln operator may apply a sealing material to the exposed ends.

Variation in the X or width direction of the board is influenced by orientation of the wood cellular structure. Ray cells in the wood transport water perpendicular to the grain more readily than vertically oriented cells. This causes the board center to be drier as illustrated in figure 2.2.2.3 (5A3) or may accentuate edge drying as illustrated in figure 2.2.2.3 (5B3). The model chosen for moisture transport represents variation in the X direction by using the average for the entire board width. Because of the drying phenomena illustrated here this model simplification has implications for selecting the apparent shrinkage threshold to be used in the model. This problem will be discussed in section 2.2.3.

The most essential aspect of the moisture content description is the gradient through the thickness or Y direction of the board. Since most of the water leaves the board through the wide face, the gradient in the Y direction has the greatest influence on the drying rate. Due to board geometry, the difference in shrinkage caused by the Y direction moisture gradient determines the moisture stresses most likely to cause residual stress and failure. Examples of this gradient for boards with tangential and radial ring orientation are shown in fig-
Figure 2.2.2.3

Plot of average moisture content versus the X coordinate of the board
Therefore, it is hypothesized that a model which predicts the average gradient in the Y direction is sufficient for control purposes. This one dimensional model will predict the drying time, the difference in shell and core moisture at the end of drying and, in combination with a one dimensional stress model, the greatest stress component. The effect of variation in moisture content on maximum stress is accounted for in the failure model discussed in section 2.2.3. The effect of variation among boards which is important in the final phase of drying can be accounted for by a model of population variance. When a model that relates variation in the board moisture distribution to the control inputs of humidity and temperature is available, optimal control can be extended through the entire drying process.

2.2.2.2 Moisture Prediction Modeling

As explained by Stamm (1964) there are three mechanisms of moisture movement: (1) bound water diffusion through cell walls, (2) vapor diffusion across cell cavities and (3) capillary flow diffusion through bordered pit membranes and microvoids in the cell walls. As explained by Bramhall (1976), there are also three distinct stages of drying. In the first stage, capillary flow to the surface is sufficient so that drying is controlled by evaporation at the surface. In practice, this stage lasts for only a matter
Figure 2.2.2.4

Plot of average moisture content versus the Y coordinate of the board
of hours. In the second stage, the surface is at some moisture content less than fiber saturation but the inner portion of the board is not. In this second stage, drying rate is controlled by bound water and vapor diffusion from the inner core to the surface. In the third stage, the entire board is below the fiber saturation point and the drying rate is decreased as the difference in moisture content between core and surface is decreased.

Since diffusion is the predominant mode of moisture transport, specifying the driving force will determine the model. The general form for the one dimensional diffusion model is:

\[
\frac{\partial M}{\partial t} = \frac{\partial}{\partial Y} \left( D \frac{\partial M}{\partial Y} \right) \quad (2.2.2.2)
\]

- \( M \) = moisture content
- \( t \) = time
- \( Y \) = coordinate of the board
- \( D \) = diffusion coefficient

The dependence of \( D \) on moisture and temperature determines whether a moisture concentration gradient or a vapor pressure gradient is being assumed. Wengert (1976) demonstrated that the diffusion model can be used very
effectively for moisture content below the fiber saturation point. Couture (1969) demonstrated the effectiveness of this model as a predictor over the entire range of moisture content. The data Couture used came from tests from McMillen's study (1955). To fit the prediction to the 140°F test, the specific gravity parameter in the equation for the diffusion coefficient had to be varied from the average value Couture originally assumed. Since adequate measurement of initial specific gravity would be too costly of time and material for an industrial situation an alternate simplified form for the diffusion coefficient was used. Disagreement of prediction and measurement is corrected by using the model optimization feature of the controller described in section 2.1.2.

If \( D \) in (2.2.2.2) is not explicitly a function of \( Y \) then

\[
\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial Y^2} \tag{2.2.2.3}
\]

If the spacial derivative is expressed by an algebraic approximation then as Chapman (1967) points out, the diffusion model becomes

\[
\frac{dM_j}{dt} = \frac{D}{\Delta Y^2} (M_{j-1} - 2M_j + M_{j+1}) \tag{2.2.2.4}
\]
where the j index refers to locations spaced ΔY apart along the direction of the Y coordinate. As explained by Chapman (1967) the form of this equation is the same as a node equation for a particular resistor-capacitor circuit. The model used in the controller (derived in Appendix A.1) is a finite difference approximation to the node equations which describes the analog circuit:

\[ M_{i+1,j} = ΔtG_j M_{i,j} + (1 - Δt(G_j + G_{j+1})) M_{i,j} 
+ ΔtG_{j+1} M_{i,j+1} \]  

\[ (2.2.2.5) \]

M = moisture content

j = position index 1, 2... 6, l = lumber plant boundary,
6 = center line of the board

i = time interval index

G_j = drying model coefficient

Δt = duration of the time interval (RW(37) in the controller computer program)

Thinking in terms of the analog model simplifies such problems as modifying the model to account for the effect of moisture on the diffusion coefficient or changing the model to account for unequal spacing of the nodes. To represent drying at the board centerline (j=6) assume
symmetric drying, that is let \( M_{i,7} \) equal \( M_{i,5} \) in (2.2.2.5).

Since, as explained in section 1.3, the lumber plant boundary is inside the board surface, drying for \( j=1 \) is also diffusion controlled. Since the position represented by \( j=1 \) is much closer to the surface than to the position represented by \( j=2 \), \( G_1 \) would have to be much greater than all other \( G_j \). This situation would force use of a short time step just to avoid numerical instability. A longer time step can be used if \( M_{i,1} \) which is largely dependent on the air humidity condition is taken to be dependent only on the air condition. That approximation allows the model for \( M_{i,1} \) to be written in a numerically stable form,

\[
M_{i+1,1} = EMC^+ (M_{i,1} - EMC) e^{-\frac{\Delta t}{\tau}} \tag{2.2.2.6}
\]

\( i \) = time index

\( EMC \) = equilibrium moisture content

\( \tau \) = lumber plant boundary drying time constant

The time constant \( \tau \) determines the plant boundary depth which is being represented by the model. If \( \tau \) is small (e.g. \( \tau = .1 \)) then the lumber plant boundary moisture content decays rapidly. This represents drying just inside the lumber surface. If \( \tau \) is large (e.g. \( \tau = 1.0 \))
then the boundary effectively dries more slowly. This corresponds more closely to the lumber plant boundary being deeper in the board which will be exposed when the wood is planed after drying.

The coefficient $G_j$ in (2.2.2.5) depends on moisture and temperature. Four trial functions for $G$ were tested: 1. An exponential form as suggested by Rosen (1976), 2. A combination of an exponential function below fiber saturation moisture and a linear function above fiber saturation moisture as suggested by Kollman (1968), 3. A polynomial of the form:

$$G_j = (\beta_0 + \beta_1 \theta + \beta_2 M_j + \beta_3 \theta M_j)^2$$  (2.2.2.7)

and 4. A polynomial of the form:

$$G_j = (\beta_0 + \beta_1 \theta + \beta_2 \theta^2 + \beta_3 \theta^3)^2$$  (2.2.2.8)

The idea of using a polynomial form for $G$ was suggested by Couture (1969). The polynomial was squared so that negative values of $G$ that might cause numerical instability would never be generated.

When the drying model was optimized, the $G$ function in (2.2.2.7) produced a better fit of the moisture prediction to the data than the other form tested. Using
the form of (2.2.2.7), the estimate of $G$ is not as readily combined with $G$ estimates determined by using other data sets if the $G$ model includes dependence on moisture content. As explained in Appendix A.3 a combination of information about $G$ is more important to control than the slight improvement in the model fit gained by including dependence of $G$ on moisture content. Therefore $G$ of the form (2.2.2.8) was adopted for the controller.

2.2.2.3 Model Optimization

Model optimization determining coefficients which minimize differences between measured and predicted in a least squares sense, is the feature of the controller that allows a simple model as presented above to effectively predict moisture content during the entire drying process. An example of how well a model optimization might fit drying data is shown in figure 2.2.2.5. All the data shown is from one of McMillen's (1955) tests. The points plotted represent the average moisture content of both slices indicated so that just as above, the model represents a symmetric drying situation. A $G$ coefficient of the form (2.2.2.8) was used but since the temperature was held constant during the test, moisture content had to be used for the independent variable. The evaluation with variable temperature is discussed in section 3.2 (see figure 3.2.7). The moisture content for slices 2 and 9 has a slight bias error but otherwise the fit is good. This might be indicative of a
Figure 2.2.2.5

Plot of prediction and measurements for the moisture transport model as optimized using all available data
Legend:
Prediction ----
Measurements:
○ Slice number 1,10
× " " 2,9
△ " " 3,8
□ " " 4,7
☆ " " 5,6

M.C. VS TIME (MCMILLEN 110F TEST)
slight problem with the piecewise linear approximation representing the true moisture content gradient near the surface.

If all the data shown in figure 2.2.2.5 is not available as is the case during an actual drying situation then the model coefficients can be determined with only a measured subset of the moisture information that is being predicted. The model optimization fit using the smallest subset, that is only the average board moisture content, is shown in figure 2.2.2.6. The data now taken routinely by the operator can easily be used to estimate the population average moisture content. The only significant difference in the result is that the core moisture prediction (levels 4, 7 and 5, 6) is poorer in the first half of the drying test. The objectives of the moisture prediction model are to predict the time history of shrinkage strain and the final moisture content. Since the prediction of final moisture content in figure 2.2.2.6 is as accurate as shown in figure 2.2.2.5, this final moisture content objective is achieved with only the average board moisture content available. Also since shrinkage does not occur until the lower half of the moisture range, the shrinkage strain time history is also predicted successfully. Therefore, the model form chosen optimized with only the average board moisture content available is suitable for control.

Summary
Figure 2.2.2.6

Plot of prediction and measurements for the moisture transport model as optimized using only the average moisture content for the board.
Legend:
Prediction
Measurements:
O Slice number 1,10
X " " 2,9
A " " 3,8
□ " " 4,7
★ " " 5,6
As explained in Appendix A.1, the moisture model used to predict the mean moisture content is a finite difference approximation to the diffusion form of the transport model. A model to predict the variance of the moisture content distribution during drying has not yet been developed. Preliminary analysis required to develop such a moisture content variance model is presented in Appendix A.2 and by Fell (1978). The effect of moisture content variance on mechanical quality in the pre-equalization phase of drying is accounted for by assumptions discussed in section 2.2.3. When the variance predictor model is completely developed and included in the controller, the automatic controller can then be effectively used for the entire drying process.

Although the diffusion form of the moisture transport model has been successfully demonstrated below fiber saturation it has never been successfully used to predict moisture throughout the entire drying process (green to 6 percent). To compensate for the inadequacies of this model and account for drying differences within a species an adaptive feature was incorporated into the controller design. That model optimization feature explained in section 2.1, is discussed further in Appendix A.3.

2.2.3 Mechanical Model

The purpose of the stress-strain model is to predict the three elements of the performance index associated with mechanical quality at the end of drying. These elements
are stress, plastic strain and frequency of failures (checking) in the lumber. The stress model finally selected for this prediction is a one dimensional lumped approximation of a three dimensional continuum mechanics model. Each approximation is explained in section 2.2.3.1. The stress-strain predictions and the model described in section 2.2.3.2 are used to predict failure. The procedures to obtain the predictions are outlined in section 2.2.3.3 and detailed in the FORTRAN listing of subroutine STRESS in Appendix 6. Having established the theoretical model, predictions generated must be checked with experimental results. The slice method of strain evaluation was used for this purpose. The technique for predicting the physical behavior of the wood when it is sliced is explained. In section 2.2.3.4, empirical data are compared with predictions of the mechanical response to drying.

2.2.3.1 Development of a One Dimensional Model

A three dimensional picture of a board is shown in figure 2.2.3.1. If there is no significant variations in shrinkage and stiffness properties in the L direction, then loading in the R-T plane for any cross-section along the length is symmetric. Since loading is symmetric, the R-T plane of the wood remains flat. As demonstrated by Sewell (1975) even strain behavior in the R-T plane at the cut end of the board where loading is not symmetric is not significantly different from strain at inner planes. For
Figure 2.2.3.1

Orientation of Cartesian and RTL coordinate systems on a board
these reasons, plane strain can be assumed thus reducing the problem of modeling to two dimensions.

The ring orientation of the board in figure 2.2.3.1 is classified as a tangential cut. Excepting boards which include the tree center or 'pith', this is the type of board most likely to develop surface checking failures. In figure 2.2.3.1, the L-T plane of the wood at board center is parallel to the top surface of the board. In this board, it is the centerline on the top surface where the highest probability of surface checking or cracking exists. Failure propensity at this point is due to the fact that shrinkage and therefore stress in the tangential (T) direction is greatest. Also stress concentration around rays when loaded in tension particularly in red oak would produce planes of weakness. Since many boards have the L-T plane parallel to the surface at some point on the wide face of the board and surface checking is the largest portion of the loss of potential lumber value due to drying, the most important stress component is in the T direction of the wood which for this example is also the X direction of the board.

The wood is piled in the dry kiln so that most of the water leaves through the top and bottom faces. As a result, the moisture gradient through the thickness is the gradient most likely to cause surface tension failure in the beginning of the drying cycle. The X component of
stress which is primarily determined by this gradient could be used to predict surface tension failure. This same stress component could also be used to predict core tension failure at the end of drying. For these reasons, a one dimensional lumped model for this most critical X direction stress was adopted and is presented in figure 2.2.3.2. The spacing of the lumped stress elements represented by the location of the subscripted symbols is closer together near the surface \( (\sigma_1, \sigma_2, \sigma_3) \). This closer spacing was chosen to more adequately represent the steep stress gradient which develops early in the drying cycle and is most often responsible for checking failure. The spacing in figure 2.2.3.2 implies a lumped element weighting factor sequence of 1, 2, 3, 6, 8, 8, 8, 4 for \( \sigma_1 \) through \( \sigma_8 \) respectively (see equation (2.2.3.1)).

Motion of the wood material due to drying is slow so that the forces due to acceleration of wood mass and damping are negligible with respect to the elastic forces due to differential shrinkage. The elastic forces must satisfy equilibrium. The board is in equilibrium if the net force in the X direction is zero. This is equivalent to saying that the total area enclosed by the stress curve in figure 2.2.3.2 is zero. If a trapezoidal approximation of the area is used, the equilibrium condition can be stated as
Figure 2.2.3.2

Diagram of node spacing for the lumped stress prediction model
Level Y=0

Stress - Compression + Tension

Y=Y_{max} Level 1 2 3 4 5

σ_{5} σ_{6} σ_{7} σ_{8} σ_{11}

σ_{4} σ_{3} σ_{2}

- Compression + Tension

Stress (\sigma)
94

\( 0 = \frac{1}{20} \left[ \left( \frac{\sigma_1 + \sigma_2}{2} \right) + \left( \frac{\sigma_2 + \sigma_3}{2} \right) + 2 \left( \frac{\sigma_3 + \sigma_4}{2} \right) + 4 \left( \frac{\sigma_4 + \sigma_5}{2} \right) \right. \)

\( + 4 \left( \frac{\sigma_5 + \sigma_6}{2} \right) + 4 \left( \frac{\sigma_6 + \sigma_7}{2} \right) + 4 \left( \frac{\sigma_7 + \sigma_8}{2} \right) \left. \right] \)

(2.2.3.1)

\( \sigma_i = \text{stress at the } i^{\text{th}} \text{ level } i = 1, 2, \ldots 8 \)

The divisor 20 appears because the half thickness \( Y_{\text{max}} \) was normalized to 1 and 1/20 is the smallest spacing used for the lumped elements. These stresses are determined by using the equilibrium equation (2.2.3.1), the geometric compatibility condition and the stress-strain relationship.

Geometric compatibility is a statement of the conditions on strain and displacement if no voids develop in the wood. The model is considerably simplified if it is assumed that \( Y-Z \) planes (board edge) remain flat. This approximation is accurate to the extent that bulging or concavity of the sides is small with respect to the total shrinkage in the \( X \) direction. The approximation is best for wide flat boards which are the boards most likely to develop failure due to the \( X \) direction stress. Geometric compatibility then requires that the total width of the board which is decreasing due to
shrinkage is constant throughout the thickness. Difference in shrinkage between the shell and the core causes extension or compression of the wood material in the X direction allowing the overall width to remain constant.

Wood does not begin to shrink until after the water in the cell cavities is removed. Subsequently, the loss of water bound in the microvoids of cell walls causes lumber to shrink. That is, as water is removed from the microvoids between cellulose microfibrils in the cell wall, the microvoids reduce in volume causing the wood material to shrink. The critical moisture content at which shrinkage begins is called the shrinkage threshold. Below this shrinkage threshold, the dependence of shrinkage on moisture content is linear as shown in figure 2.2.3.3. For an unrestrained (no moisture gradient) wood element, the shrinkage threshold is equal to the fiber saturation point (cell wall saturated, no water in cell cavity).

In the situation where a gradient of unrestrained shrinkage exists in the thickness direction as it does in the drying board and the material remains geometrically compatible then as discussed in section 1.1 and depicted in figure 1.1.2 tension and compression exist in the shell and core levels. When using the average moisture content to predict the average shrinkage strain of a slice, the shrinkage threshold is at fiber saturation only if the moisture content is constant through the entire width. In practical applications, such a distribution never occurs
Figure 2.2.3.3

Shrinkage strain versus moisture content showing shrinkage threshold
Shrinkage strain

Shrinkage threshold

0

Moisture content (%)

(%)
because edge drying causes a gradient in the width direction which is superimposed on the gradient through the thickness. To illustrate this, an example of the moisture distribution for a low rate of edge drying is shown in figure 2.2.3.4A with the equivalent shrinkage distribution shown in figure 2.2.3.4B. Note that when the average moisture content at \( Y = Y \) is above the fiber saturation point, the average shrinkage is non-zero. For a similar slice having the same average moisture content but from a board with a higher rate of edge drying as shown in figure 2.2.3.4C a greater portion of the board is shrinking and the average shrinkage in figure 2.2.3.4D is therefore greater than for the previous example. Thus, average shrinkage at any point \( Y = Y \) for a given slice average moisture content is greater when edge drying is more pronounced. This effect is accounted for in the one dimensional model by increasing the shrinkage threshold while holding the maximum shrinkage strain constant.

The edge drying rate of boards is influenced by the thickness to width ratio, the amount of edge exposure and the roughness of the board edge. All boards considered in this study ranged from 2 X 4 to 2 X 6 inches. Since the relative edge drying rate depends also on geometry, narrower boards may even develop the gradient shown in figure 2.2.3.4D at low edge drying rates. Tests by McMillen, taken during an experimental study designed to gather data for a drying prediction model, represent maximum
Figure 2.2.3.4
Diagram showing the effect of two different edge drying rates on average shrinkage for a given average slice moisture content.
Shrinkage strain

Moisture content (%)

Board

Less edge drying

More edge drying

X (Width coordinate)

Difference shrinkage strain

Legend

Average

Board edge

Wide surface
edge drying because all edges were exposed directly to the air stream. This corresponds most to the drying situation where air impinges directly on the exposed edge of the boards on the leading edge of a pile and the boards are loosely piled. In order to obtain data which corresponds more closely to the drying found inside the kiln load, the sample boards used in drying tests at UNH were edge-planed and tightly packed to form the trailing edge of the pile. After each periodic test a sample was taken, the board was reversed so that the alternate edge was exposed. Therefore, the effective shrinkage threshold for in-pile drying is lower than for the completely exposed board used by McMillen. Although the drying situation is not directly related to the in-pile drying situation, McMillen's study does provide the most complete set of data for checking the predictive ability of the model.

The final relationship needed to determine the stresses for the lumped model depicted in figure 2.2.3.2 is the relationship of stress to strain. The instantaneous component of the stress-strain behavior is predicted by a hysteresis model. An example of loading and then unloading along the hysteresis curve when the stiffness properties are held constant is shown in figure 2.2.3.5. The instantaneous behavior is then defined by the maximum and elastic limit values of the stress and strain material properties.
Figure 2.2.3.5

Loading-unloading of the hysteresis stress-strain model showing the memory strain component
These properties are functions of temperature and moisture content. Using multiple regression techniques, Youngs' (1957) experimental study provided algebraic models to predict these properties if the moisture and temperature are known. The form of the model for all the parameters is

\[ Y = A + B\theta + C \cdot M + D(M)^2 + E \cdot \theta \cdot M + F \cdot \theta^2 \cdot (M)^2 \]

(2.2.3.2)

\( Y \) = parameter predicted (maximum stress, elastic stiffness etc.)

\( A, B, \ldots F \) = regression coefficients

\( \theta \) = temperature

\( M \) = moisture content

This model is detailed in 'FUNCTION Y' of the program listing of Appendix 6. The coefficients A through F are stored in 'FUNCTION STIFF' for the modulus of elasticity 'FUNCTION SIGEL' for elastic limit stress, 'FUNCTION SIGMAX' for maximum stress and 'FUNCTION EPSMAX' for maximum strain.

The technique for estimating the plastic memory strain using the hysteresis model is called the 'Incremental Process' and is outlined by Manson (1968). Briefly, this process involves making an under-estimate and an over-estimate of plastic memory strain at each time step. These
two estimates are averaged and the resulting estimate is tested. If the tested estimate is greater than the true value then the over estimate value is updated. Conversely, the under-estimate is replaced if the estimate is too small. The average is again calculated and the estimation cycle is repeated until the desired convergence is obtained. The set of relationships is too extensive to present here but the entire process is derived in Appendix A.4.

The rheological (time dependent) behavior of the samples tested by Youngs (1957) is presented in figure 2.2.3.6 showing the creep test response. This test is accomplished by hanging a deadload on the wood specimen and measuring the strain behavior over time then removing the weight and measuring the recovery strain.

As discussed previously, the hysteresis model defines the stress-strain relationship for the spring. The stress-strain relationship for the dashpot is

$$\frac{d\varepsilon_{\text{VEM}}}{dt} = \beta \sigma$$

(2.2.3.3)

$\sigma = \text{stress}$

$\beta = \text{viscous (creep) constant}$

$\varepsilon_{\text{VEM}} = \text{viscous memory strain}$

For the model that was adopted, the constant $\beta$ is the slope of the actual measured creep response curve at
Figure 2.2.3.6

Actual response of the wood and simulated response of the modified Maxwell model to the creep test
Maximum creep strain component
Elastic-plastic strain component

- Actual wood response
- Model response
36 hours into the test divided by the stress applied. Youngs tested red oak samples cut across the grain at four moisture-temperature test conditions for periods of 72 hours each. Six stress levels were applied at each of the four conditions. The viscous coefficient calculated from these tests was reasonably independent of stress level so that for a given moisture and temperature condition the average could be determined. The resulting four values are the coefficients for the empirical equation.

\[
\beta = \beta_0 + \beta_1 M + \beta_2 \theta + \beta_3 \theta M
\]  

(2.2.3.4)

\(\beta\) = viscous constant  
\(M\) = moisture content  
\(\theta\) = temperature  
\(\beta_0, \ldots, \beta_3\) = algebraic coefficients which are listed in the listing of 'SUBROUTINE VISCOM' in Appendix 6

The viscous strain is calculated by a stepped integration of (2.2.3.3). The time step for the integration should be small with respect to the shortest time constant for the Maxwell model and is
\[ \tau = \frac{1}{\beta E} \quad (2.2.3.5) \]

\[ \tau = \text{time constant} \]
\[ \beta = \text{viscous constant} \]
\[ E = \text{stiffness} \]

The shortest time constant during drying is approximately 10 hours, therefore the 2.4 hour time step chosen is sufficiently short.

The Maxwell model will predict infinite strain for a constant stress but the wood will not support this infinite strain. This limiting or maximum creep strain can be accounted for by adding a parallel spring element to the Maxwell model thereby converting it to a standard model. This approach was abandoned in favor of using a parallel hard limiting device instead of the spring. This modified Maxwell model depicted in figure 2.2.3.6 provides a reasonable prediction at a great saving in computer time.

The one dimensional model is then solved by first using the shrinkage (see figure 2.2.3.3), the geometric compatibility condition and the equilibrium condition (equation 2.2.3.1) to determine the stress at each level represented by the lumped model. These stress values are then used to determine the change in viscous strain at each time step. The procedure is discussed in section 2.2.3.3.
2.2.3.2 Failure Prediction Model

The model for predicting failure is the most important of all the prediction models because failures (surface checking and honeycombing) produce the greatest value loss in drying hardwood lumber. Unfortunately, the failure phenomenon is the least understood of the mechanical responses of wood to drying conditions. Two models to predict failure were considered. The first model, suggested by Cousins (1974) based failure on the maximum stress the material can withstand. The second model, suggested by Byvshykh (1960) predicts tensile failure by calculating the ratio of tensile work to the maximum tensile work which is the product of maximum stress and maximum strain. The factors which affect the maximum stress and strain and tensile work are moisture content, temperature, time and other factors related to wood structure. The effects of these factors on wood drying were assumed to be distributed normally about a mean value.

The model to predict the maximum drying stress for comparison with the maximum allowable stress is an extension of the symmetric model presented in figure 2.2.3.2. Youngs (1957) provides the most extensive data set for predicting maximum stress and strain at failure for various kiln drying conditions. Most of the data on failure from Youngs (1957) is for short term tensile tests run at strain rates two orders of magnitude greater than the rates experienced
during drying. As suggested by Cousins (1974), provision was made in the model to multiply the maximum stress by a constant factor (see RW(229) in the documentation section of the program listing of Appendix A.6) to account for the effect of the difference in strain rate on this stress limit. Very few failures were experienced by Youngs during the creep test so that RW(229) was determined by comparison of the failure model prediction to data taken in the UNH study.

The maximum or failure limit stress (FLS) used for the failure prediction is reduced by prolonged heating of wet wood. The FLS could drop to less than one half of its original value during the higher temperature phase of drying. In order to have a predictor compatible with the finite difference format, an exponential model to predict loss of strength with time was fit to Youngs (1957) experimental data. This model seemed to fit the data as well as the fractional power model Youngs used. Failure is most likely to occur at the location of maximum stress. Therefore the failure is estimated by comparing the maximum stress to the FLS. The one dimensional lumped model presented in figure 2.2.3.2 is designed to predict only the average stress for each level and the counter-part level on the bottom half of the board. The discussion which follows describes a method of predicting maximum stress. The shrinkage differential between the R and T directions causes a distortion of the rectangular shape of the board.
in the R-T plane during drying. This effect is called cupping and is illustrated in figure 2.2.3.7. Cupping is caused by greater shrinkage on the bark side or top face of the board due to the nearly tangential (T) orientation of the growth rings as compared with the pith side or bottom face in which the R axis of the board is more nearly aligned with the X axis of the wood. This distorted shrinkage distribution results in an asymmetric drying stress distribution that is equivalent to the sum of the symmetric moisture stress component predicted by the lumped model and a bias stress distribution as illustrated in figure 2.2.3.7. Thus the resultant surface stress may be significantly different than the surface stress value predicted by the symmetric model. If the board were isotropic, this cupping distortion is the same distortion that would be produced by a constant bending moment about the Z axis. Therefore, the linear bias stress distribution illustrated in figure 2.2.3.7 was assumed. However, only the maximum bias stress is needed to specify the distribution. This maximum stress was determined experimentally by making measurements of the cupping deflection and using the deflection formula for a long prismatic member subjected to a constant bending moment (see section 3.1).

Other nonmeasurable differences in wood structure that may affect the FLS can be accounted for by hypothesizing a distribution of FLS about an assumed mean, namely that of the model prediction. Differences in ring orientation
Figure 2.2.3.7

Cupping distortion and the associated model stress components
Moisture stress + Bias stress = Resultant stress
because of their effect on the bias stress also affect the loading stress (LS) distribution used for failure prediction. These wood property differences that cause the variation in LS and FLS are modeled as random variables distributed about the mean. Examples of the LS and FLS distributions are presented in figure 2.2.3.8 where the failure event is defined. If the LS distribution is assumed to be a relatively tight distribution then it can be modeled by an impulse function and if the FLS distribution is assumed to be close to normal then the cumulative distribution function for failure (CDFF) can be assumed to be as depicted in figure 2.2.3.9 where for the stress failure model

\[
CDFF = \text{MAXIMUM } \frac{\sigma_j + \sigma_{\text{bias}} - \sigma_{\text{MFLS}}}{\sigma_{\text{AFLS}} - \sigma_{\text{MFLS}}} \frac{1}{2}
\]

(2.2.3.6)

CDFF = Cumulative Distribution Function for Failure
\(\sigma_j\) = stress as depicted on figure 2.2.3.2,  
\(j = 1,2,3\)
\(\sigma_{\text{bias}}\) = bias stress
\(\sigma_{\text{MFLS}}\) = minimum failure limit stress (see figure 2.2.3.9)
\(\sigma_{\text{AFLS}}\) = average failure limit stress (see figure 2.2.3.9)
Figure 2.2.3.8

Probability density function of loading and failure limit stress distributions showing typical failure events.
Probability density

Loading stress (LS)

Failure limit stress (FLS)

Failure event (a)

FLS < LS

Stress (PSI)
Figure 2.2.3.9

Cumulative Distribution Function for Failure (CDFF) based on stress failure model
Minimum Average
Stress (Psi)

failure limit
stress CMFLS

Average failure limit
stress CMFLS

Percent failure

Simplified model

Model

Stress (Psi)
The cost calculated according to the simplified model in figure 2.2.3.9 is purposely designed without an upper limit. This was done so that unrealistic trial schedules tested during the schedule optimization search would generate excessively large estimated drying costs. This aids in the optimization search and has no effect on the final solution where the CDFF is much less than 100 percent failure. The average failure limit stress (σ_{AFLS}) is predicted using the model from Youngs (1957) as expressed in formula (2.2.3.1). The minimum failure limit stress (σ_{MFLS}) and the multiplication factor discussed by Cousins (1974) must be determined by optimizing the model prediction to measured failure. This optimization is done by using slice strength data from Drying Test 3 (DT-3) which ran according to the standard schedule (see section 3.1).

A second model of the same form as the first but substituting tensile work (i.e. cumulative tensile stress multiplied by incremental tensile strain) for stress as suggested by Byvshykh (1960) was also tested. This work limit failure model provided a better fit to the experimental data than the maximum stress failure model. Also during the computer evaluation, the optimized schedule produced using the work limit model resulted in a more conservative solution. For these reasons, Drying Test 4 (DT-4) used for the controller evaluation (see section 3.2)
was based on a work limit failure criteria.

2.2.3.3 Model Solution Procedure

A flow chart for the calculations involved in the simulation of wood drying is diagrammed in figure 2.2.3.10. Prior to entering the loop, initial moisture content, control input EMC and temperature are set. All this information is required for the initial prediction of stress and strain. However, stress prediction also requires an update of unrestrained shrinkage strain at each of the eight levels using the moisture content and the shrinkage model depicted in figure 2.2.3.3. The wood mechanical properties are then estimated using a model from Youngs (1957) in the form of formula (2.2.3.2). The change in stress state is then calculated using an elastic-plastic type of model as depicted in figure 2.2.3.5 according to the procedure detailed in Appendix A.4. The failure due to this new stress state is then estimated using (2.2.3.6) or a model of the identical form based on the work limit criteria. The viscous memory strain increment is calculated using (2.2.3.5). If the model results are only to be used for schedule optimization then step 6 of the stress-strain prediction procedure of figure 2.2.3.10 is skipped. The predicted mechanical measurements such as release strain and prong deflection are only calculated if needed for comparison with data. The details of this stress prediction can be found in the listing of subroutine STRESS in
Figure 2.2.3.10
Block diagram showing the sequence of calculations required to predict stress output and mechanical drying costs
SET INITIAL CONDITION:
Model Moisture Content (M.C.)
Control Inputs

PREDICT STRESS AND STRAIN:
1. Update Shrinkage Strain
2. Calculate Wood Mechanical Properties
3. Calculate Instantaneous Change in Stress State
   A. Assuming no change in plastic deformation
   B. Estimating low limit increment of plastic memory
   C. Estimating upper limit increment of plastic memory
   D. Refining estimate till negligible error
4. Estimate Failure
5. Estimate Rheological Component of Strain
6. Calculate Model Outputs (such as Release Strain, Slice Deflection, etc.)

UPDATE TIME DEPENDENT COSTS:
1. Heat Loss
2. Failure

ADVANCE:
Time Step

TEST FOR END OF DRYING:
Is Average M.C. Equal to Desired Target Value?

YES
DROP SIMULATION TEMPERATURE TO 80°F
CALCULATE FINAL STRESS
CALCULATE FINAL COSTS
CONVERT PHYSICAL COST VALUES INTO ECONOMIC EQUIVALENTS

MODEL CALCULATION FLOW CHART
Appendix 6.

After the stress prediction is complete, the time dependent costs of heat loss and failure prediction are updated. The heat loss is calculated as a simple summation of the heat lost at each interval. The failure estimate is updated only if the ratio of work or stress to the limit for that variable has increased above the previous maximum value.

If the average moisture content is at or below the target value, the calculation procedure exits the loop to calculate the stress distribution at room temperature and the economic cost. If not, the time step is advanced, the control inputs for that time are determined and drying continues. This information and the moisture state at the previous time step are all that are needed for the moisture prediction model (section 2.2.2) to predict the moisture content for the next cycle.

If on the other hand as indicated above, the target moisture content has been attained the board stress distribution is recalculated for room temperature ($80^\circ F$). This drop in temperature alone can cause the stress distribution in the board to change because different thickness levels in the board are at different moisture contents and will show different gains in stiffness due to temperature change. The cost of drying is then calculated using the economic model (section 2.3)
2.2.3.4 Model Prediction of Physical Measurements

Models become valuable only when verified by experiment. The elements of a predicted response that are important to drying are moisture content, stress, memory strain and percentage of failure. Unfortunately, no single empirical drying study exists in which all these parameters were measured simultaneously.

McMillen (1955) includes simultaneous measurement of moisture content, release strain and relative shrinkage. Release strain indicates stress and relative shrinkage indicates plastic memory strain. The model prediction of moisture distribution compared to data from McMillen was evaluated in section 2.2.2. Model prediction of release strain, that is, dimensional changes in slices when cut free from a sample block plus shrinkage will be evaluated in this section. No information is available on percent failure (surface checking) from McMillen (1955) since no quantitative measurements were made.

The UNH experiments include simultaneous measurement of moisture content, slice release strain, slice deflection after cutting, and surface checking failure. The measurement of slice deflection was accomplished separately from the release strain on an adjacent block sample according to the industry prong deflection test procedure illustrated in figure 2.2.3.11. The measurement of prong deflection can be used to estimate the gradient of the stress in the
Figure 2.2.3.1

Prong section test and cantilever beam model used for quantitative analysis of prong deflection
Prong section

Cantilever beam model for prong

Pure bending stress distribution within the prong
prong and the adjacent slice for which the average axial release strain component is measured. The stress responsible for surface checking can only be estimated by using both the average slice (prong) stress and the stress gradient. A simple cantilever beam model is used to predict slice (prong) deflection due to the moisture gradient. The elastic stress distribution in the slice or prong is taken to be the sum of two components. The average value component of stress causes axial extension or contraction when the slice or prong is cut. If the remaining component is represented by the stress distribution shown in figure 2.2.3.11 i.e. equivalent to a constant bending moment, then the maximum stress \( \delta_{\text{max}} \) is estimated by using the deflection of the prong end \( \delta_{\text{MAX}} \) and the model for a long prismatic member under a constant bending moment (Crandall (1959)).

\[
\delta_{\text{max}} = \frac{M_0 \cdot L^2}{2E \cdot I}
\]

(2.2.3.7)

\( \delta_{\text{max}} \) = deflection of the end of the prong  
L = length of the prong  
E = average prong stiffness based on moisture content, temperature and the stiffness model equation (2.2.3.2) from Youngs (1957) work.
I = moment of inertia of the cross-sectional area of the prong

\[ M_0 = \text{bending moment} \]

For the stress distribution shown in figure 2.2.3.11

\[ M_0 = \frac{\delta_{\text{max}} \cdot b \cdot h^2}{6} \]

\[ b = \text{prong width} \]

\[ h = \text{prong thickness} \]

\[ \delta_{\text{max}} = \text{maximum stress} \]

and

\[ I = \frac{b \cdot h^3}{12} \]

so that combining equations (2.2.3.7, 8, 9) and solving for \( \delta_{\text{max}} \)

\[ \delta_{\text{max}} = \frac{\delta_{\text{max}} \cdot E \cdot h}{L^2} \]

(2.2.3.10)

The prong deflection (\( \delta_{\text{max}} \)) is one of the outputs calculated as part of procedure 6 of the stress-strain prediction. The only quantitative data available to verify the prong deflection prediction are the measurements from UNH tests which are compared with the prediction in section 3.2.

The other output calculated as part of procedure 6 of the stress-strain prediction is average release strain. The release strain which is measured by cutting blocks
into thin slices can be calculated by using the board width before cutting and subtracting the measured long dimension of the slice after cutting.

\[ \varepsilon_{\text{release}} = \frac{L_1 - L_2}{L_1} \]

(2.2.3.11)

\[ \varepsilon_{\text{release}} = \text{strain equivalent of instantaneous deformation experienced on cutting} \]

\[ L_1 = \text{board width dimension before cutting} \]

\[ L_2 = \text{slice long dimension after cutting} \]

(see figure 2.2.3.12)

The drying model does not generate \( L_1 \) directly but predicts the total strain from the original green dimension. That is, the total strain is the total elastic-plastic strain component plus the creep component of strain. When cutting the slice, only the total elastic-plastic component changes. However, the after cutting measurement is made before any significant creep relaxation has occurred. This strain component released by slicing the block (release strain = elastic component) can be estimated by resolving the equilibrium equation for just that portion of the board included in the slice. The equation of equilibrium for the entire board is in Appendix A.4. The reduced form for slice 1 is stated here as an example:
Figure 2.2.3.12

Diagram illustrating block sample before and after slicing to determine average strain
Before slicing

\[
\begin{array}{c}
1 \\
2 \\
3 \\
4 \\
5 \\
6 \\
7 \\
8 \\
9 \\
10 \\
\end{array}
\]

\[L_1\]

After slicing

\[
\begin{array}{c}
1 \\
2 \\
3 \\
4 \\
5 \\
6 \\
7 \\
8 \\
9 \\
10 \\
\end{array}
\]

\[L_2\]
\[ \varepsilon_{BN} = \frac{1}{4} \sum_{j=1}^{4} (\varepsilon_{SRC_j} + \varepsilon_{VEM_j} + \varepsilon_{EPM_j}) \cdot E_{1j} \cdot C_j \]

\( (2.2.3.12) \)

\[ \varepsilon_{BN} \] is the strain at the slice boundary with respect to the original dimension in the green condition.

\( \varepsilon_{SRC} \) = source strain due to shrinkage which drives the whole mechanical process.

\( \varepsilon_{VEM} \) = viscous memory strain.

\( \varepsilon_{EPM} \) = plastic memory strain.

\( E_{1j} \) = elastic stiffness.

\( C_j \) = stress weight array element which is different for the slice than it was for the board.

(2.2.3.1)

for slice 1, \( C_1 = 1 \), \( C_2 = 2 \), \( C_3 = 3 \) and \( C_4 = 2 \).

\( j \) = position index.

The measured recoverable strain is then

\[ \varepsilon_{elastic} = \varepsilon_{BN \text{ (board)}} - \varepsilon_{BN \text{ (slice)}} \]

(2.2.3.13)
because the \( L_1 \) divisor is implicit in the model prediction.

The permanent memory component of strain, plastic deformation, was not measured directly by McMillen but an indication of this deformation can be inferred from his total shrinkage data (green to ovendry). If there were no plastic deformation, the total shrinkage at all slice levels would be equal. Consequently, if there are differences in total shrinkage between slices then plastic deformation has occurred. The procedure for estimating this shrinkage is similar to that used to estimate recoverable strain. The equilibrium equation estimates the average strain for the slice from green to ovendry. This version of the equation now has the form:

\[
\varepsilon_{BN} = \frac{\sum_j (\varepsilon_{VEM} + \varepsilon_{EPM}) \cdot E_{1j} \cdot C_j}{\sum_j E_{1j} \cdot C_j}
\]

(2.2.3.14)

\( \varepsilon_{BN} \) = deviation in shrinkage for each slice from the case of the slice with zero plastic deformation (according to McMillen this condition is approximated in slice 2)

Release strain data from McMillen and the model prediction (solid line) are plotted in figure 2.2.3.13 to illustrate the prediction error if zero edge drying is
Figure 2.2.3.13

Release strain data and model prediction (solid line, shrinkage threshold = 30 percent) for McMillen 110°F test
Legend

○ Shell
× Core

STRAIN VS TIME (MCMILLEN 110F TEST)
assumed (i.e., shrinkage threshold equals 30 percent). The large disagreement is explained by the fact that McMillen surfaced all four faces of each board and exposed all to drying air so that significant edge drying did occur. Edge drying in this case is significantly different from the edge drying that occurs when boards are tightly placed edge to edge as in normal dry kiln operations. The result is that the prediction is more conservative after 30 days because the predicted strain exceeds the measured strain causing the predicted stress reversal to occur later (54 days) than the empirical data indicates (40 days).

In order to evaluate the predictive capability of the different components of the model, the shrinkage threshold must be adjusted so that the prediction agrees as well as possible with the McMillen data. The release strain prediction using a shrinkage threshold of 60 percent is plotted (solid line) with the same empirical data in figure 2.2.3.14. It is apparent that the agreement between empirical data and prediction is much improved. However, the post-reversal release strain value is too low. A prediction using the same model is compared with data from another McMillen experiment run at a constant temperature of 140°F (see figure 2.2.3.15). This is the highest temperature used in McMillen's work and represents model predictive capability in the upper half of the temperature range used to dry red oad. The model under-estimates post stress-reversal release strain more severely
Figure 2.2.3.14

Release strain data and model prediction (solid line, shrinkage threshold = 60 percent) for McMillen 110°F test
Strain vs Time (McMillen 110°F Test)

Legend
- ○ Shell
- × Core

Time (Days)
Strain vs Time (McMillen 110°F Test)
Figure 2.2.3.15

Release strain data and model prediction (solid line, shrinkage threshold = 60 percent) for McMillen 140°F test
Legend

○ Shell
× Core

Strain vs Time (McMullen 140°F Test)
than the previous comparison. An underestimate of release strain indicates that the average stress in that slice is lower than the predicted value.

The average predicted release strain in the post stress-reversal period is low because the creep strain predicts a greater viscous flow thus relieving more stress than is actually released. If the viscous strain prediction is plotted (figure 2.2.3.16), it may be seen that the shell strain increases sharply for the first 2 days and then stays constant from 2 to 14 days because the viscous strain model has reached the hard limit for the predictor model (figure 2.2.3.6). The hard limit or maximum viscous strain component was determined after careful examination of Youngs (1957) data and is assumed to be proportional to the elastic strain component. It is observed that both the shell and core strain begin decreasing between 14 and 15 days. If this decrease does not occur then the magnitude of the release strain after stress reversal will be much greater.

One way to test this hypothesis is to eliminate the viscous strain memory portion of the model and again compare the empirical data and the prediction. That comparison is presented in figure 2.2.3.17 (solid line). Elimination of the viscous memory was accomplished by setting the hard limit value to 0.01 of the normal creep limit. This in effect forced a larger plastic memory component. Since much higher stress is required to erase
Figure 2.2.3.16

Viscous strain prediction (shrinkage threshold = 60 percent) for McMillen 140°F test
Viscous strain vs. time (McMillen 140°F test)
Figure 2.2.3.17

Release strain data and model prediction (solid line, shrinkage threshold = 60 percent) with the viscous strain component suppressed.
Legend

○ Shell
× Core

STRAIN VS TIME (MCMILLEN 140F TEST)
the plastic memory, the predicted post-reversal stress must reach a much greater value. As may be seen, this stress is such that the predicted release strain agrees well with the data. However, the change in the model caused the pre-reversal release strain to increase because the viscous strain had not acted to relieve the initial stress buildup required to maintain geometric compatibility. This suggests that only the predicted post-stress reversal viscous strain is in error. The prediction of the viscous creep rate depends on two variables, moisture and temperature. However, data for only four combinations of these variables was available. Therefore, even though a better viscous memory prediction model is necessary, it can only be accomplished when more than four experimental data points are available. Since the predicted response in figure 2.2.3.17 suggests that a plastic model may be sufficient, additional data may never be necessary.

The remaining component of the model which can be evaluated through use of McMillen's data is the plastic memory component. The plotted data points from McMillen in figure 2.2.3.18 represent the difference in total shrinkage between the shell and core slices and slice 2. This slice 2 shrinkage is taken as a reference because it experiences the lowest maximum stress and is therefore least likely to be plastically deformed. The set-strain prediction (solid lines) for the core significantly disagrees with the empirical data after 12 drying days.
Figure 2.2.3.18

Set strain data and model prediction (solid line, shrinkage threshold = 60 percent)
Legend

○ Shell
× Core

SET STRAIN VS TIME (MCMILLEN 140F TEST)
The data points suggest that the core set continues to increase until approximately 18 days. The model predicts no increase in core set after 12 days. Model prediction of plastic memory is consistent with the fact that the core stress does not increase after 12 days as evidenced by the behavior of the release strain plotted in figure 2.2.3.17. Since the difference between predicted and observed set strain is not plastic it would have to be accounted for by a viscous memory model. It is also possible that this difference is the result of an artifact introduced as a result of experimental procedure. Experience in tests at UNH suggests that even when using McMillen's procedures, it is difficult to oven dry the slices for shrinkage determination without introducing bending distortion. After drying, the slice is more brittle in addition to being more distorted so that flattening the slice to measure the arc length with the dial guage is difficult to achieve without fracturing the slice. This bending distortion would tend to make the measured after drying length an underestimate and may explain the observed discrepancy. If further research indicates a need, this question should be answered by further investigation of the viscous property of wood under kiln drying conditions as well as development of an improved technique of set strain determination.
Summary

Since the predictor model is to become part of the optimization algorithm, the model should be economical of required computer time. A given schedule optimization may require several hundred complete drying cycle predictions. To simplify the stress-strain relationship a piecewise linear approximation was used. The experimental viscous memory behavior shown in the creep tests by Youngs (1957) suggests that a standard model (series spring and dashpot all in parallel with a second spring) best simulates the creep phenomena. A standard model was approximated by using the series spring-dashpot Maxwell model with a hard limit. The hard limit was taken to be proportional to the elastic strain component so as to simulate as nearly as possible the effect of the parallel spring. This simplification allowed a simple stepped integration procedure to be used for calculating viscous strain thus greatly reducing the calculations required to account for the dynamic element of the model.

The amount of calculation for the lumped model approach was reduced by a significant amount when a one dimensional approximation to the 3 dimensional board was used. Although the most significant stress component is in the X direction, edge drying does affect the X direction stress level. This was accounted for by simply increasing the shrinkage threshold. The shrinkage relationship is
important because predicted stresses are very sensitive to the shrinkage model used. Before further improvement in this model can be achieved an accurate two dimensional moisture prediction will be needed. For the present, adjustment of the shrinkage threshold produces reasonable results.

When the one dimensional symmetric board model was first tested, the predicted failure rate was far lower than the measured rate. This problem was corrected by accounting for the asymmetry of wood drying with a bias stress model. The bias stress model for failure prediction is identical to the model illustrated in figure 2.2.3.11 which is used to predict prong deflection. The cupping distortion deflection (figure 2.2.3.7) was determined from experimental measurement (see section 3.1).

The prediction of prong deflection was included in the model because as explained in section 1.3.4 this measurement is important for effective control. Also, this is the only mechanical measurement that can be made accurately in the industrial system as it now exists. Prong deflection prediction will be compared with empirical data in section 3.2.

The original plan for evaluating the automatic kiln control scheme was to first develop the model as presented in figure 2.2.3.17. A test run using the present standard industrial control strategy was to then be run. Measurements from this test were to have been used to
establish the shrinkage threshold for the actual drying situation and establish the coefficients for the failure model. Unfortunately, some of the measurements from the conventional control strategy test and the analysis presented here were not available when it was necessary to perform the computer test evaluation so that the test was run using the model as presented in figure 2.2.3.13.

For the next test (DT-5), the analysis suggests that until the creep memory model can be improved, it should be excluded from the prediction. This is accomplished by setting a very low maximum creep strain limit. This modification will tend to produce a conservative prediction before stress reversal similar to that shown in figure 2.2.3.17. The initial stress prediction will be high so surface tensile failure is not underestimated and post reversal stress will be accurate so residual stress is realistically estimated.
2.3 **Economic Model - Performance Index**

The economic model is the remaining piece of the puzzle needed to completely specify the problem. It is the economic expression which reduces the diverse drying costs and qualify degradation to common terms so that a drying cost can be determined. The objective of automatic control is to dry the lumber according to a schedule that minimizes the cost of drying. The definition of this drying cost or performance index as it is called by control theorists is the subject of this section.

2.3.1 Cost Categories

The costs associated with a drying schedule fall into three categories: 1. energy, 2. fixed costs and 3. loss of potential lumber quality. The energy cost is due to heat lost through the kiln walls, ceiling and floor. An energy cost such as electricity used to drive the fan motors is considered one of the fixed costs since this energy loss rate is constant and not affected by temperature or humidity selected. Other fixed costs include labor, taxes and cost of equipment. The loss in potential quality is divided into four sub-categories: 1. moisture distribution, 2. residual stress, 3. plastic strain and 4. tensile failure.

Deviation of final wetness from target value in any
portion of the lumber population is the first sub-category of potential quality loss. Wood that is wetter or dryer than the desired equilibrium moisture content in the final product could lead to a shrinking or swelling distortion once the wood has been included in an expensive piece of furniture or other high value product.

Residual stress is the second sub-category of loss in potential lumber value. Residual stresses will result in distortion immediately after the lumber has been machined. Boards may warp, making assembly difficult or pinching the saw blade when being cut.

The third sub-category of quality loss is total plastic deformation. The average final width of the board is a function of the average plastic deformation. Therefore, the selling price of the board as it is affected by the final volume depends on the drying history.

Failure, the last of the four quality sub-categories represents loss in potential value that cannot be improved by further conditioning. Once the board is severely surface checked, its furniture value is lost. However, surface checked lumber not suitable for furniture, may still be used in the construction of pallets used to ship furniture and heavy machinery.

Other forms of mechanical distortion such as board twist, crook and bow (longitudinal bending distortion of the board) also reduce final lumber quality. These factors are not included in the economic analysis since these dis-
tortions depend on longitudinal variation of board properties not affected by the schedule and therefore are not directly controllable by the schedule inputs.

2.3.2 Cost Conversion

Conversion of energy or heat loss drying cost has already been discussed in section 2.2.1. The cost conversion coefficient $K_1$ in equation (2.2.1.1) can be determined if the temperature difference integral

$$
\theta_1 = \int_0^T (\theta - \theta_0) \cdot dt
$$

(2.3.1)

$\theta_1$ = temperature difference integral (degree days)
$\theta$ = kiln temperature (degrees F)
$\theta_0$ = ambient temperature (degrees F)
$T$ = final time (days)

and the associated dollar cost are known for a past schedule. The coefficient $K_1$ is then calculated according to

$$
K_1 = \frac{HC}{\theta_1}
$$

(2.3.2)

HC = economic cost of heat expressed as a fraction of the potential dry value of the lumber (no units)
Using a simulated standard industrial schedule to estimate $\theta_1$ and determining the associated economic cost by an industrial telephone survey (1977) the heat cost conversion coefficient is

$$K_1 = \frac{.054}{3500} \text{ (degrees F - days)}$$

$$= 1.54 \times 10^{-5} \frac{1}{\text{degrees F - days}} \quad (2.3.3)$$

The cost conversion for the fixed cost is determined in a similar manner.

$$FC = K_2 \cdot T \quad (2.3.4)$$

$FC =$ fixed cost expressed as a fraction of the potential dry value of the lumber (no units)

$K_2 =$ cost conversion coefficient \(\frac{1}{\text{days}}\)

$T =$ total drying time (days)

The conversion coefficient $K_2$ was also determined in a similar manner from the industrial telephone survey (1977).

$$K_2 = \frac{.086}{90 \text{ days}}$$

$$= 9.56 \times 10^{-4} \frac{1}{\text{days}} \quad (2.3.5)$$

Estimating the lumber value loss is more difficult. Final value of the board is determined by an in-
spectator who assigns a grade. The dollar worth of lumber by grade is published periodically in local economic bulletins. Dollar value difference between one grade and another is termed the "Grade Drop Value" (GDV) which is the value loss that would occur if the loss in potential value due to drying defect caused the inspector to rate the board one grade lower. The degradation necessary to cause this loss in value is termed the "Grade Drop Threshold" (GDT). With the exception of the failure cost, the economic cost for the quality loss category is

\[ EC = Q \cdot \frac{GDV}{GDT} \]

EC = economic cost expressed as a fraction of the potential dry value of the lumber

\( Q = \) final quality expressed in terms of moisture content, residual stress or plastic strain

The GDV can be determined as the average difference of value in grades. An average value of

\[ GDV = .2 \]

(2.3.7)

was determined by averaging differences between "Price Relatives" from a commercial bulletin.

The most logical approach to specifying the desired final quality (\( Q \)) and the GDT would be to use industry
standards for moisture content, stress and plastic strain. Unfortunately such precise quantitative industrial standards do not exist. In the absence of constraints, the form of Q was then chosen to facilitate the optimization search. The classical quadratic form for the performance index was used. Therefore Q for final average moisture content is

\[ Q(M(T)) = (M(T,\text{shell}) - TM)^2 + (M(T,\text{core}) - TM)^2 \]

\[ Q = \text{final quality factor} \]
\[ M(T,\text{shell}) = \text{final moisture content in the shell} \]
\[ TM = \text{target moisture content} \]

(2.3.8)

The associated GDT was determined by a simulation of the standard schedule.

\[ \text{GDT} = 13.9 \]

(2.3.9)

so the first of the four quality factors is

\[ K_{3a} = \frac{\text{GDV}}{\text{GDT}} = \frac{.2}{13.9} = 1.44 \times 10^{-2} \]

(2.3.10)

Originally the Q for the residual stress cost was defined in the quadratic form but the calculated cost seemed to be out of proportion to the other costs even for reasonable schedules so the cost function was modified.

\[ Q(\text{residual stress}) = \sum c_j |\sigma_j(T)| \]
(2.3.11)

\[ C_j = \text{stress weights resulting from the equilibrium equation } j = 1,2,\ldots,8 \]

\[ C_j = \{1,2,3,6,8,8,8,4\} \]

\[ \sigma_j(T) = \text{stress at the final time (residual stress)} \]

The associated GDT calculated by the same simulation is

\[ \text{GDT} = 9764 \frac{\text{lb}}{\text{in}^2} \]  

(2.3.12)

So that the second of the four quality factors is

\[ K_{3b} = \frac{2}{9764} = 2.05 \times 10^{-5} \frac{\text{in}^2}{\text{lb}} \]  

(2.3.13)

The Q for strain is of the same form as equation (2.3.11) for the same reason. The GDT for strain from the same simulation is

\[ \text{GDT} = .2030 \]  

(2.3.14)

So that the third of the four quality factors is

\[ K_{3c} = \frac{2}{.2030} = .985 \]  

(2.3.15)

The economic model adopted for the failure cost is based on the model that was described in section 2.2.3.2. The Q for failure is an estimate of the percentage of the
population with surface checking failures to the depth that renders the board completely unsuitable for furniture application. Therefore the fourth of the final quality conversion factors used is

\[ K_{3d} = 1.0 \]  

(2.3.16)

The total cost is then the sum of all the above costs or

\[ DC = K_{1} \cdot T_{1} + K_{2} \cdot T \]
\[ + K_{3a} \cdot (M(T,\text{shell}) - TM)^2 + (M(T,\text{core}) - TM)^2) \]
\[ + K_{3b} \sum_{j} |\sigma_j(T)| + K_{3c} \sum_{j} |e_{EPM}(T)| \]
\[ + K_{3d} \cdot \text{CDFF} \]  

(2.3.17)

\[ DC = \text{Drying cost (no units)} \]

Summary

The economic model presented is in a form suitable for any hardwood drying situation. The economic conversion coefficients can be calculated for species other than red oak by using the procedures outlined in this section.

Now that the relative desirability of the individual elements of final quality can be quantified, a drying schedule can be determined that will optimize characteristics of final lumber quality most important for a given application. This capability should result in less waste
of time, energy and material. The optimization scheme is described in section 2.4.
2.4 Optimization Algorithm

If the set of cost components in the economic model for the cost of drying (see section 2.3) is comprehensive and the weighting coefficients used best represent the relative importance of these components then the best drying schedule possible (air temperature and humidity versus time) produces the lowest calculated drying cost. The method of determining this best schedule is the subject of this section.

The total heat loss, final time, moisture content, stress, memory strain and total failure estimate are all needed to determine the drying cost. These estimates are obtained from a complete schedule simulation. The schedule specification technique is determined by the approach used to search for the minimum cost or optimum drying schedule.

There are two approaches to optimizing the drying schedule. The first, called the function approach, is a modification of a method used to optimize algebraic models. The function approach was used to optimize the drying schedule for the controller test described in section 3.2. The second, called the variational approach (Appendix A.5), is the method classically used by designers to determine control inputs for dynamic systems. Although this second optimization approach usually results in a more efficient
search algorithm or procedure, the rate of development of
the control system may be hindered since every change in
the form of the model causes a change in the search pro­
cedure. Therefore, a working control system was developed
using the function approach described in this section.
Future research may be directed at making the controller
more efficient by application of the variational approach.

In order to use function optimization techniques,
the cost of drying must first be converted to a function.
A function is defined in the following way.

"Let A and B be sets and let there be
given a rule which assigns exactly one member
of B to each member of A. Then the rule,
together with the set A is said to be a function
and the set A is said to be its domain. The
set of all members of B actually assigned to
members of A by the rule is said to be the range
of the function." (Allen (1960))

The set B is the set of all drying costs. If the
schedule, which is a continuous time history of two inde­
pendent variables, temperature and humidity, could be
specified by a single point then the point would be from
set A. One point, however, is not sufficient to describe
the schedules. Several points from independent domain
sets A_1, A_2, ..., A_n are needed. As the number of indepen­
dent points required to specify the schedule increases,
the efficiency of the search procedure decreases. There­
fore it is advantageous to use the minimum number of
points to specify a schedule.
The schedule could be defined by discrete steps as it is prescribed now. Stepped schedules are designed to minimize the operator effort required for control. If a machine is used to perform the control function, then a more efficient continuously variable input can be used and the drying rate is more precisely controlled over the entire drying interval. Also, the large transient stress that occurs at a step change can be avoided.

A smooth schedule defined by a set of points is therefore desirable. The input could be described as a Fourier series that would require specification of the amplitude and phase of the sine components. If the optimum is not periodic with time, the schedule is more efficiently specified as an interpolation of temperatures and humidities at predetermined times. A Lagrange interpolation scheme as discussed by Kuo (1972) was adopted so that the input is defined as

\[ u_j(t) = \sum_{k=1}^{n_j} \prod_{i \neq k}^{n_j} \frac{t - t(i)}{t(k) - t(i)} u_j(k) \]

(2.4.1)

\[ u(t) = \text{input value at time } t \]
\[ u(k) = \text{one of the 'k' input values which is interpolated to specify the schedule} \]
\[ n_j = \text{number of points required to specify an input} \]
\[ j = \text{index of input variable} \]

1 specifies EMC

2 specifies dry-bulb temperature

\[ n = n_1 + n_2 \] is the number of independent points required to specify the function input.

The value of \( n \) is also the dimension of the function input space that is searched by the optimization algorithm.

In the present design any number of points \( n (n \geq 4) \) may be used to specify a schedule. For the drying tests described in section 3.2, ten points were used. Five points specified the air temperature time history and five specified EMC.

The Lagrange interpolation scheme is well suited to dealing with constraints on the control inputs. The temperature of conventional versus high temperature wood drying equipment is constrained to be above 80°F. The wood EMC is constrained to be greater than zero but less than 20 percent. An unconstrained schedule is first constructed according to formula (2.4.1). The constraints are accounted for by using the following trigonometric transformation

\[ u'(t) = \frac{u_{\min} + u_{\max}}{2} + \frac{u_{\max} - u_{\min}}{2} \sin(u(t)) \]

(2.4.2)
\( u'(t) = \) actual input schedule in degrees fahrenheit and percent EMC

\( u_{\min} = \) minimum value of the input

\( u_{\max} = \) maximum value of the input

\( u(t) = \) unconstrained version of the schedule in radians or degrees

The function input is then completely determined by the \( u(k) \) from the \( k \) independent domain sets.

Although the actual function space is 10 dimensional, a 3 dimensional visualization is useful to understanding the optimization techniques. The function value is represented by the height of the surface \( (z) \) for a given set of coordinates \( (x \text{ and } y) \). The objective of the optimization technique is to search the set of \( x - y \) coordinates which represent the function input to find the lowest point on the surface \( (z) \). This search could be conducted randomly (monte carlo method) or systematically. The systematic methods require fewer function evaluations and are therefore more efficient. One systematic method is to evaluate coordinates at regular spacings (regular grid method). If the gradient (the vector tangent to the surface) is available, then even more efficient optimization techniques are available to guide the search to the lowest point on the surface. If the second function derivative is available then even more powerful techniques can be used (for example Newton Raphson) when the search has been carried
to the vicinity of the minimum. Unfortunately, only the function value is available so that a direct search technique is used. The technique adopted after an evaluation of direct search techniques was the Simplex Method of Nelder and Mead (1965).

In the Simplex technique, the down hill direction is estimated by projecting a line through the coordinates of the highest of the set of \( n + 1 \) (\( n \) = dimension of function input) calculated function values and the centroid of the coordinates of the remaining \( n \) points of the simplex. A step is taken along the line and if the function value is lower, the highest point is replaced by that point. The details of how long the step is and whether the alternate contraction procedure is used are detailed in the article by Nelder and Mead (1965).

Since the transformation (2.4.2 was used, the drying cost function is repetitive with a period of \( 2\pi \).

\[
    u'(t) = u'(t) + 2m\pi \quad m = 1, 2, \ldots, l
\]

(2.4.3)

That is, the function surface for the transformed problem is periodic with period \( 2\pi \) for all \( n \) dimensions. If the distance between the vertices of the simplex does not become small with respect to \( 2\pi \) then the simplex search will avoid small local minima. When in the course of the
search, the function values associated with every simplex vertex become nearly equal and the simplex begins to contract then the search could be converging on the minimum. The search is terminated when the RMS (root mean square) value of the differences of the function values for all the vertices falls below a preset threshold. The coordinates of the optimum are estimated as the centroid of the simplex coordinates.

The disadvantage of the simplex method is that the optimum location estimate is sometimes too imprecise. The precision depends upon how steeply sloped the surface is and how small the simplex. For the wood drying optimization problem the precision and consistency was checked by using several randomly generated schedules as starting points for the search. The majority of solutions that resulted agreed to a precision within the control tolerance for most commercial kilns (±2°F dry bulb temperature, ±1% EMC) and the remaining searches produced a poorer result. The simplex technique was also evaluated on classical problems similar in form and complexity to the wood drying problem with known analytical solutions. The conclusion is that the simplex technique is suitable for development of the research version of the optimal controller.

Flexibility is an important advantage of the function approach. By defining the function as the RMS prediction error for the moisture model, the model optimi-
zation discussed in section 2.2.2.3 was accomplished using the Simplex optimization algorithm. The coordinates of the simplex vertices represent trial sets of moisture model coefficients. By using the function approach for model optimization several forms of the drying model can be tested without redesigning the search algorithm.

Summary

The decision to use the function approach for optimization was strongly influenced by the desire for flexibility. This control design is still in the early research stage and using the function approach allows for modular design of the optimization system software. This form of the optimization system was made possible by the Lagrange interpolation representation of the input schedule. With this system, the form of the drying models can be changed completely without affecting the design of the optimization subroutine of the computer program. This flexibility was of benefit since the same algorithm is used to identify the drying model coefficients. If reliable data is available, the same subroutine could conceivably be used to identify unknown stress model coefficients.

The simplex algorithm was chosen since it always tends toward a minimum even for poor initial guesses. The most important question is global optimality. Is the minimum the lowest of all the local minima? This is answered by the simplex search technique producing essen-
tially identical answers for completely different sets of randomly generated starting points.

The model optimization is usually accomplished with less than 2 minutes of CPU (central processor unit) time on the UNH Dec-10 computer. Generation of a schedule requires in excess of 30 CPU minutes. For most commercial installations, a more efficient program will be needed. Prior to industrial implementation of the controller, the optimization system will need to be improved. A primer for development of a more efficient algorithm is presented in Appendix A.5.
3. TEST EVALUATION OF CONTROL STRATEGY

The test evaluation of the optimal controller had to be conducted in two phases. Previous studies lacked critical information, so the first phase, described in the following section 3.1, was primarily designed to determine missing parameters for the prediction model. The second phase test (DT-4) reported on in section 3.2 demonstrated the performance features of the controller. Since it was desirable for the two phases to use material with similar drying characteristics the two charges were taken from 48, 2 by 5½ inch 16 foot boards from butt and upper red oak logs selected from UNH lands. These boards were cut into 8 foot end-matched boards and mixed to provide two kiln charges of nearly equal characteristics.

3.1 Phase One - Model Information

In a commercial drying situation, information from previous drying runs is used to improve the drying models. Studies by McMillen (1955) and Youngs (1957) supplied the basic information for our models. The test (DT-3) described in this section supplied information necessary to complete the model.

The industry standard schedule (Rasmussen (1961)
schedule T3D1 for 8/4 red oak) of temperature and humidity was used as the basis but modification had the effect of accelerating the test. This procedural change (see section 3.1.2) resulted in a much higher than normal failure rate providing more measurements than normal for comparison with the failure prediction.

3.1.1 Sampling Plan

The lumber for DT-3 was sawn from 16 foot logs of seven red oak trees grown in the locality of Durham N.H. The 16 foot boards were each cut in half. One half of each board was marked and randomly segregated into two endmatched groups of lumber. One pile was prepared for drying (DT-3), the other dead piled, wrapped in polyethylene and covered with snow to await the following test (test DT-4 discussed in section 3.2). For DT-3, twelve boards of the 48 to be dried were selected for longitudinal sampling. These twelve boards were separated into two groups of six each consisting of three sets of two boards representing each of the three principal ring orientations (tangential, radial and oblique). During drying, each group of six was sampled once per week alternating in three or four day cycles.

Each board sample consisted of one block one inch in length sampled for moisture content and release strain and an adjacent block sampled for stiffness tests. The end sampled was reversed every other week. Only slices
1,5,6 and 10 as depicted in figure 2.2.3.12 were sampled since only the shell and core information is needed to verify the prediction.

3.1.2 Test Results

Using the average moisture contents determined from the twelve samples cut each week, the drying model coefficients were optimized according to the procedure discussed in section 2.2.2.3. A plot of the average moisture content data and prediction (solid line) are presented in figure 3.1.1.

In an industrial situation, the coefficients derived from this optimization would be combined with the information from previous drying runs of the same species and thickness. The method of combining this information is discussed in Appendix A.3. Since DT-3 and DT-4 (see section 3.2) were run with matched lumber, the drying rate coefficients used for the initial schedule optimization of DT-4 were based solely on the coefficients used to produce figure 3.1.1. The coefficients are presented in table A.3.1.

Estimates of stress in the wood during this test required that the stiffness (E) of individual slices be known. The stiffness models presented by Youngs (1957) in the form (2.2.3.2) could only be used if the red oak in tests DT-3 and DT-4 was not significantly more or less stiff than Youngs' samples. Actual slice stiffness was
Figure 3.1.1

Data and prediction (solid line) for moisture content using optimized coefficients of average shell and core moisture content for DT-3.
Legend

○ Shell
× Core

MOISTURE CONTENT

H.C. VS TIME (DT3)
determined by loading each one to failure in tension perpendicular to the grain in a model TT-D Instron Universal Testing Machine using a strain rate equal to that used by Youngs (.037 in/min) and load ranges of 200 or 500 pounds. Test results are presented in table 3.1.1. For a 95% confidence interval on approximately 15% of the predicted value, the predicted results did not differ significantly from the measured results for all three ring orientations. For this reason, Youngs (1957) model was used to predict the stiffness (E) for the DT-4 schedule optimizations.

When all other model parameters have been determined then the shrinkage threshold is set by matching the predicted release strain to the measured strain and to the prong deflection data. Sampling boards in the center of the charge to determine the most appropriate threshold would have required excessive sampling time thus disrupting the schedule. The rough cut and loosely fit edges of boards in industrial drying practice do dry significantly so that sealing edges against moisture loss would produce too low an edge drying rate. Therefore, to simulate in-pile drying as nearly as possible, the board edges were planed smooth allowing a tight edge to edge fit. The boards on the trailing edge of the pile when sampled were replaced with the alternate edge exposed to balance the edge drying. Since the release strain measurement technique used in DT-3 provided unreliable results, the actual shrinkage threshold was not established until
Table 3.1.1

Experimental measurement of Modulus of Elasticity (lbs/in$^2$) for shell and core slices sampled in DT-3
<table>
<thead>
<tr>
<th>Ring Orientation</th>
<th>Low * Confidence Limit</th>
<th>Prediction Youngs (1957) Model</th>
<th>Upper * Confidence Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangential</td>
<td>56,381</td>
<td>63,000</td>
<td>65,135</td>
</tr>
<tr>
<td>Radial</td>
<td>82,393</td>
<td>110,000</td>
<td>111,215</td>
</tr>
<tr>
<td>Oblique</td>
<td>57,850</td>
<td>61,000</td>
<td>66,446</td>
</tr>
</tbody>
</table>

* 95% Confidence limit (80°F, Moisture content greater than 30 percent) of data taken during the test.
after analysis of DT-4 results in which the McMillen slicing technique was used. A shrinkage threshold of 30 percent was therefore assumed for purposes of optimizing the schedule for DT-4.

The stress prediction model directly estimates final stress and plastic strain. Indirectly, this predicted average stress and a bias stress are used to predict the maximum stress for failure. The model for the bias stress as discussed in section 2.2.3.2 is represented by equation (2.2.3.10) where \( \sigma_{\text{bias}} = \sigma_{\text{max}} \). The measured deflection distortion for the entire board cross section called block deflection is plotted (points) in figure 3.1.2. Using the model for a long prismatic member, (2.2.3.10), the average deflection for both groups is estimated by the plotted linear model response (solid line).

\[
\sigma_{\text{bias}}(0) = \frac{\delta_{\text{max}} \cdot E \cdot h}{L^2}
\]

\[
= (.25) \cdot (120,000 \text{ psi}) \cdot (2 \text{ in}^2) \\
= \frac{(6 \text{ in})^2}{(6 \text{ in})^2}
= 1667. \text{ psi}
\]

(3.1.1)

\( \sigma_{\text{bias}}(0) \) = bias stress for zero moisture content

\( \delta_{\text{max}} \) = estimated from figure 3.1.2

\( E \) = estimated stiffness at zero percent
Figure 3.1.2

Data and linear model interpolation (solid line) to predict block deflection which determines the bias stress used for failure prediction.
GROUP 1 X
GROUP 2 0

AVERAGE MOISTURE CONTENT (%) vs BLOCK DEFLECTION (DT3)
moisture content

\[ h = \text{thickness of board (block sample)} \]
\[ L = \text{width of board} \]

To use this bias stress for failure prediction, failure must first be defined. To provide a measurable basis for failure it was defined as any check that caused a shell or core slice to break during the process of slicing or measuring release strain. Since such failures would disqualify the wood for furniture applications, the definition is both realistic and measurable.

The measured value of the CDFF (section 2.2.3.2) at the end of DT-3 was .7 (7 of 10 boards; 2 boards were excluded because they failed prior to drying). The high failure rate seemed to have three possible causes. The first, that step changes in temperature and humidity were based on the average wetness of the sample boards, whereas the Kiln Operator's Manual suggests that changes should be based on the average of the wettest half of the sample boards. Therefore, the step changes were made sooner than intended by the standard schedule. The net result was that the wood dried in two thirds the normal time. The second cause for high failure was that the airflow rate (380 to 480 feet per minute) was higher than prescribed by the schedule (i.e. 200 to 400 fpm). The resulting steep gradient of moisture content very near the surface may have caused a steep shrinkage gradient.
which was in part responsible for the observed surface checking. The third probable cause for high failure was that the humidity at the beginning of the test was lower than specified due to failure of a wet bulb sensor. Although the CDFF was higher than intended, the data is still very valuable for determination of the minimum failure limit stress (or work).

The average failure limit is predicted by a model of the form (2.2.3.2) using coefficients from Youngs (1957). Models using both stress and work failure limits were tested. The low limit values were expressed as a fraction of the average failure limit. Plots of failure data and prediction for both tests are presented in section 3.2. Since the strain rate due to drying (less than $10^{-7}$) is outside the range tested by Cousins (1974), no information is available on the effect of strain rate on failure strength. Different factors were tried but a factor of 1.0 was used to produce the failure simulations presented in section 3.2.

Summary

With the exception of the shrinkage threshold the phase I test (DT-3) successfully established the model coefficients for the computer controller technique evaluation test (DT-4). Failure to adequately measure the release strain provided no empirical data for estimating the shrinkage threshold. As a consequence the threshold
had to be anticipated and was set at 30 percent. Because of this difficulty, however, the release strain technique was refined in DT-4 so that successful strain measurements could be made and a more realistic value of shrinkage threshold for the in-pile drying situation was estimated.
3.2 Phase Two - Computer Controller Test

3.2.1 Test Objective

Tests seldom produce exactly the results the designer expects. The phase two test (DT-4) was originally designed to determine the best lumber quality economically possible using conventional drying equipment, the computer controller and a human kiln operator. Delay of DT-4 prolonged the period of lumber storage and altered the lumber drying characteristics of the charge. Moreover a pretest modification to the kiln changed the temperature and humidity control limits. These two unforeseen developments, detected after the test had begun, prevented a best quality possible result but did provide the opportunity to test the effectiveness of the adaptive features of the controller design.

3.2.2 Test Procedures

The phase two test was used to refine the actual control procedures and will be discussed in section 3.2.2.2. Details of the control procedures and the computer program used are documented in Appendix A.6. Success of these control procedures is presented graphically in section 3.2.3. Procedures for obtaining the data plotted in these graphs is discussed in section 3.2.2.2.4.
3.2.2.1 Experimental Measurement Procedures

As described in section 3.1, the lumber for DT-4 is matched to the lumber used for DT-3 and, therefore, was prepared simultaneously in February. The matched lumber for DT-4 was tightly piled, wrapped in plastic and buried in snow. Because the storage location received little direct sunlight, the snow covering persisted late into the spring. When the snow covering was lost, a foil wrapper was added to keep the pile cool and a sprinkler inside the wrapper continually wet the lumber surface. Even though the lumber surfaces were also treated with clorox (or industrial detergent) and water to inhibit bacteria growth, some slime did develop.

A kiln charge of 48 red oak boards 2 by 5$\frac{1}{4}$ inches by 8 feet long was selected for DT-4. The narrow faces or edges of all boards were surfaced so that they would fit tightly together in the pile. Twelve of the sixty were selected for periodic sampling. Four of the twelve boards had radial ring orientation, four tangential and four oblique (45° with respect to the x axis). A $\frac{1}{2}$ inch sample block was cut at a distance of one inch from each end of every board. These samples were weighed and dried to establish the initial moisture distribution. A histogram of that distribution is illustrated in figure 2.2.2.1. The average is wetter than expected. This high average is due to end absorption of water during the long storage
period.

Prior to beginning and at predetermined times during the test, each of the twelve boards was sampled by removing paired one inch blocks at a point two inches from one end. One block was used to determine the moisture and release strain distribution by the slice method. The other block was used for the standard prong test. To obtain the sample from each board, the kiln was first shut down. Then the blocks were cut, tightly wrapped in vinyl film, and heat sealed in plastic tubes. Each sample board was recoated with a commercial end-sealer, Sealog by Lukon Inc. immediately after cutting. Because a change in wood temperature causes a redistribution of stress, the sealed blocks were returned to the kiln environment prior to measuring and slicing. The prong test blocks were also tightly wrapped in vinyl film and then set aside for cutting.

Blocks for slicing were removed from the kiln one at a time. The block was marked for slicing as illustrated in figure 2.2.3.12. A very small hole was drilled in the ends of each slice numbered 1, 5, 6 and 10 as shown in figure 3.2.1 to receive the tip of the measuring anvil. Then length $L_1$ was measured for all four slices before cutting by using a dial gage. The slices were then cut along the marked lines and each pressed into a spring loaded retainer to straighten it for a dial gage measurement of length $L_2$ as illustrated in figure 3.2.1. The
Figure 3.2.1
Dial gage and slice restraint device for measuring the average elastic strain component in a slice
block at the top of the figure has been sliced and is ready for measurement with slice 1 removed for positioning in the dial gage. The enlargement at the bottom of the figure shows an end view of the retainer holding a slice and an enlargement of the anvil which was inserted into the slice.

After the strain measurements were completed, the moisture content of each part of the block was determined by the oven drying method. By consistent procedure and keeping slices wrapped prior to tests, moisture loss during measurement was kept to a minimum.

The information provided by the slice tests permits estimation of the moisture gradient in the board. However, the gradient in the shell slice so critical to predicting surface checking failure, can only be estimated if prong deflection data is available. To facilitate prong deflection measurement, photo copies were made of each block before and after cutting using an IBM Copier II. An example of these before and after pictures is shown in figure 3.2.2.A and B. The prong deflection was measured by superimposing the two copies on a light table and measuring the deviation to the nearest .01 inch with an engineering scale and hand lens. Due to the physical distance between the photo copy equipment and the bandsaw, the total time for making a photorecord of the prong deflection was approximately 30 minutes. The blocks were allowed to cool before cutting and measuring because it
Figure 3.2.2

Block and prong section photocopies used to measure the gradient of elastic strain by the prong deflection method.
would have been impractical to maintain the blocks at kiln temperature. Close agreement between empirical data and predicted deflection at kiln temperatures as illustrated in figure 3.2.9 reinforces the hypothesis that the temperature loss has little effect on the net bending moment (gradient) within a slice.

The measurements (slice length and prong deflection) can only be converted to equivalent stress values if the stiffness and its relation to moisture and temperature are known. It was established during DT-3 that the stiffness of the red oak used was not significantly different from that predicted by Youngs' (1957) model. Therefore the formula (see equation (2.2.3.2)) and coefficients (see lines 2292 and 2293 of the program listing of Appendix A.6) from Youngs' (1957) work were used to predict stress for failure.

3.2.2.2 Computer Control Procedures

An important result derived from evaluation of DT-4 was the refinement of the procedures for using the optimal computer control algorithm. The six procedures:
1. Initial schedule optimization, 2. Sensitivity analysis,
6. Schedule update are discussed below and explained in more detail in Appendix 6.
3.2.2.2.1 Initial Schedule Optimization

After the economic and drying model coefficients have been determined (see section 2.3), the first procedure is the schedule optimization. Normally, the procedure for determining the drying model coefficient, as discussed in Appendix A.3, would utilize drying information from all available tests of the same species and thickness. Since the DT-3 test used lumber matched to the DT-4 lumber, the model optimized to the DT-3 drying data was used to perform the initial schedule optimization for DT-4. Since the minimum temperature used in DT-3 was 110°F, data from McMillen's (1955) study was used to extrapolate the drying coefficient down to 80°F.

The process of determining the 'initial' schedule shown in table 3.2.1 involved five optimization searches using the stress limit model to predict failure and nine optimization searches using the work limit model to predict failure. Each search was independent because each began with a different set of random schedules initiated by a data file similar to that illustrated in figure A.6.2. More searches were conducted with the work limit model because it produced a more conservative solution. The initial EMC, at 0 days in the schedule, was under 10 percent for the stress limit fail criteria solution whereas that EMC value was close to 20 percent for the work limit failure case. Consequently a focused search was conducted.
Table 3.2.1

Schedules Used During DT-4
### SCHEDULE 1: (INITIAL SCHEDULE)

<table>
<thead>
<tr>
<th>EMC</th>
<th>20.0</th>
<th>16.4</th>
<th>14.7</th>
<th>4.6</th>
<th>6.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMPERATURE</td>
<td>121.0</td>
<td>94.0</td>
<td>86.0</td>
<td>154.0</td>
<td>133.0</td>
</tr>
<tr>
<td>TIME</td>
<td>0.0</td>
<td>20.0</td>
<td>40.0</td>
<td>60.0</td>
<td>80.0</td>
</tr>
</tbody>
</table>

### SCHEDULE 2: (IMPROVED INITIAL SCHEDULE)

<table>
<thead>
<tr>
<th>EMC</th>
<th>20.0</th>
<th>16.4</th>
<th>14.7</th>
<th>4.6</th>
<th>6.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMPERATURE</td>
<td>121.0</td>
<td>94.0</td>
<td>80.0</td>
<td>154.0</td>
<td>133.0</td>
</tr>
<tr>
<td>TIME</td>
<td>0.0</td>
<td>20.0</td>
<td>40.0</td>
<td>60.0</td>
<td>80.0</td>
</tr>
</tbody>
</table>

### SCHEDULE 3: (UPDATE SCHEDULE)

<table>
<thead>
<tr>
<th>EMC</th>
<th>16.9</th>
<th>13.3</th>
<th>7.9</th>
<th>2.2</th>
<th>4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEMPERATURE</td>
<td>121.0</td>
<td>123.0</td>
<td>175.0</td>
<td>122.0</td>
<td>141.0</td>
</tr>
<tr>
<td>TIME</td>
<td>30.0</td>
<td>42.0</td>
<td>54.0</td>
<td>66.0</td>
<td>78.0</td>
</tr>
</tbody>
</table>

### UNITS

- **EMC** (PERCENT MOISTURE CONTENT)
- **TEMPERATURE** (DEGREES FAHRENHEIT)
- **TIME** (DAYS)
Using the work limit criteria the best solution of the first seven searches served as a pivotal schedule for the initial random schedules of the focused search which were limited to ±5 percent EMC and ±20°F of this pivotal schedule. The best of the focused searches produced the initial schedule in table 3.2.1.

3.2.2.2 Sensitivity Analysis

According to the procedure for the simplex optimization algorithm, the search is halted when the sum of the squares of the differences between the drying costs of all the trial schedules and the average drying cost agree to within a prescribed tolerance. This criteria does not guarantee a minimum cost of drying, therefore, the resulting initial schedule was tested. The test consisted of changing each EMC and temperature one at a time and calculating the drying cost. If any change produces a lower cost schedule than the original search, then the prescribed procedure is to initiate a focused optimization using the changed schedule as the pivotal schedule. Since time was limited, the prescribed procedure was not followed. The pivotal schedule listed as schedule 2 in table 3.2.1 was used for DT-4 without modification. The schedule optimization procedure has since been completely automated so that it can be accomplished efficiently as discussed in Appendix A.6.

The recommended procedure is to run at least three searches and take the best answer of the three as a pivotal
schedule for the focused search and then run a schedule sensitivity analysis on the result of the focused search perturbing the EMC ±1 percent and the temperature ±2°F. Since these are control tolerances for the inputs to the lumber plant, the optimum does not have to be known any closer than this. If the schedule fails the sensitivity analysis, then the focused search or the initial search is reinitiated.

3.2.2.2.3 Simulation

The form of the schedule as it exists prior to simulation is depicted in table 3.2.1. This form of the schedule may be step interpolated as conventional schedules are or continuously interpolated by a Lagrange formula of the form (2.4.1). The smoothly varying schedule may be printed out at half day intervals after a simulation has been performed. During the controller test the kiln was adjusted once per day to conform with the smooth schedule. Considering the number of changes and time to readjust the kiln, the actual schedule could be approximated by a smooth varying component plus control noise. The output of the simulation may include any information available from the model such as moisture content, release strain and prong deflection. Instead of including a listed copy of the complete DT-4 schedule, the initial schedule is plotted as a solid line in figures 3.2.5 and 3.2.6.

The simulation not only produces a completed schedule to guide the operator but it also transforms a controller
program into a learning tool. The user may start and stop the simulation at any simulated time (see lines 68 through 85 of the program listing in Appendix A.6) and examine any model coefficient or physical state. If the user desires, he may change any coefficient or state and proceed with the simulation (see section A.6.1.3 of Appendix A.6). This simulation procedure was used during the schedule update procedure for DT-4 to produce an estimate of the state of the update time. The update procedure is discussed in section 3.2.2.2.6.

3.2.2.2.4 Graphics

Although a plotting capability is not necessary to the control function, the graphics feature is extremely valuable. The graphics mode is entered interactively during or after simulation. The results of any combination of variables written into the output file is plotted on a terminal, a printer or a graphics terminal (see section A.6.1.4 in Appendix A.6).

To illustrate the use of this technique in model development, a plot of the initial prediction of moisture versus time used for DT-4 is shown in figure 3.2.3. The model coefficients used for this moisture prediction were derived from data taken during the previous test, DT-3 which used lumber end-matched with that of DT-4. The procedure for deriving these coefficients is explained in section 2.2.2 and Appendix A.3.
Figure 3.2.3

Prediction of M.C. (solid line) for the initial schedule (schedule 2 of table 3.2.1) and measured data for the computer controller evaluation test
Legend

○ Shell
× Core

M.C. vs Time (DT4 Initial Prediction)
In figure 3.2.3 the measured moisture content data from DT-4 is plotted for comparison with the prediction (solid line). The prediction does not agree well with the observed data. Since the lumber used in DT-3 was end-matched to that of DT-4, one might expect a better fit. It is likely that the extended storage conditions for DT-4 lumber may have altered the lumber drying characteristics.

The lumber used for DT-3 was wrapped in polyethylene film and covered with snow at subfreezing temperatures until removed for drying. The lumber for DT-4 remained in storage well into the summer months using a sprinkler to maintain wetness. It appears this storage condition altered the normal initial condition for the lumber. Therefore, a difference in initial wetness, as well as alteration in permeability due to bacterial growth, two effects of storage, may have contributed to the difference between measured and predicted moisture content.

The different drying schedules for DT-3 and DT-4 constitute different treatments of the lumber. If the drying coefficient were completely correct, this difference would not contribute to disagreement between the prediction and the data. The fact that the form of the drying coefficient excluded dependence of the drying rate on moisture content probably contributed significantly to the disagreement. The reason for this disagreement is discussed in Appendix A.3. Effective inclusion of the dependence of drying rate on moisture content is future research will eliminate much
of the disagreement between the initial prediction and the observed moisture content.

3.2.2.2.5 Model Optimization

The large difference between initial prediction and moisture content data in figure 3.2.3 allows the opportunity to demonstrate the effectiveness of two very important facets of the controller design. The first is model updating and the second is state estimation. As will be explained in section 3.2.2.2.6, this controller is designed to use schedule information and the model to infer those states not measured. State estimation is performed after the model identification procedure described in this section and in section A.6.1.5 of Appendix A.6 has established the moisture prediction coefficients.

If the algebraic form chosen for the drying coefficient is fundamentally correct and if the drying model perfectly describes the drying time constant, then the optimization only needs to be done once for each wood species and lumber thickness combination. The diffusion form for the drying model used as the basis for the simple finite difference model is the best predictive model available. Diffusion is, however, far from a perfect description of moisture transport in wood. Even if diffusion were an adequate model, the diffusion coefficient or its equivalent here called the drying coefficient \( G \) are influenced by moisture content and anatomical differences within a wood
species. Anatomical differences are often characterized by specific gravity and ring angle of the wood. Both of these influences (moisture and anatomy) are excluded from the form of the drying coefficient (2.2.2.8) used in DT-4. Since the specific gravity measurement is very time consuming and destructive of material it was not included as input for the prediction of the drying coefficient because this test is designed to simulate an industrial situation. Although it is readily available, the moisture content information was not used successfully for a drying coefficient prediction. The problem encountered was that for the algebraic multinomial model tested (equation 2.2.2.7), extrapolation produced physically unrealistic values of the drying coefficient. As discussed in Appendix A.3, extrapolation of the assumed cubic relationship between the drying time constant and the temperature could be corrected if necessary.

Extrapolation of the drying coefficient model was required for the initial model optimization in DT-4. The drying coefficient which resulted from optimizing the drying model to the DT-3 data was not monotonically increasing with temperature below 110°F. This can occur as it did for the DT-3 data when the temperatures used (110°F to 160°F) did not extend over the entire available temperature range (80°F to 180°F). The extrapolation was corrected by using the data from McMillen's (1955) study and the procedure described in Appendix A.3. A second model optimization was performed for the schedule update (see figure 3.2.4).
3.2.2.2.6 Schedule Update

The update procedure, which is an ordered execution of the five procedures just discussed, illustrates one of the most important features of the feedback controller. As a result of the update process, the estimate of the state of moisture content and stress is improved. In addition, the estimate of the drying rate coefficients is also refined. Finally, a better prediction of the remainder of the drying cycle is made.

Schedule update was accomplished twice during DT-4 using the procedures outlined in section A.6.1.5; 1.) a few days into the test to adjust the schedule for a miscalculation of initial wetness and 2.) at a test time of 32 days (schedule 3 of table 3.2.1) to adjust for divergence of data and prediction as well as account for a higher than expected low limit for the dry bulb temperature.

To illustrate the update procedures, the second update will be reviewed. The process was started 2 days earlier (at 30 days) so that the new schedule would be ready for the projected schedule switchover time at 32 days. Model optimization was performed first as described in section 3.2.2.2.5. The second procedure was to simulate the test run (DT-4) from the initial time to the projected switchover time. Final values of wetness and stress were saved on a file as a starting point for the schedule optimization procedure that was to follow. The resulting optimi-
ized schedule was checked using the sensitivity analysis procedure. The moisture content prediction for this schedule as simulated is plotted in figure 3.2.4 along with the measured data for the entire test. The accuracy of the update prediction can be compared to the accuracy of the original prediction by examining figure 3.2.3 and 3.2.4. Improvement in the prediction is the result of effective utilization of measured information in the feedback loop. The complexity of the wood drying phenomenon and our inability, therefore, to model it faithfully, means that feedback correction is essential for accurate control.

The schedule used during the simulation for the update was a step approximation of the air temperature and humidity data taken during the test. During the simulation the lumber plant boundary was set close to the surface \((\tau = .1)\) to produce an upper limit estimate (more conservative) for failure.

It is possible that this procedure produced an overestimate of the failure that may have biased the updated schedule. For example, suppose the actual failure of the population were 50 percent but the simulation procedure produced an estimate of 100 percent failure then no update schedule, no matter how severe, would produce any further failure. Therefore, the resultant schedule would be unaffected by the failure cost, possibly causing an increase in the actual failure.

In retrospect, a less severe update schedule
Prediction (solid line) and data for schedule update at 32 days into the computer controller evaluation test
Legend

○ Shell
× Core

MOISTURE CONTENT

TIME (DAYS)

M.C. VS TIME (DT4 SCHEDULE UPDATE 32 DAYS)
(more slowly rising temperature) may have resulted if the optimization starting state was based on a low-limit estimate of failure. The failure estimate that results from simulation can be made smaller by moving the lumber plant boundary in from the surface (i.e. $\tau = 1.0$) and then using a fifth-order time polynomial approximation of the actual schedule. This 'smoothed' schedule is obtained by doing a polynomial regression on the temperature and EMC data. The regression can be accomplished with any standard statistical computer program such as the National Bureau of Standards Minitab 2 statistical program used here. The schedule is simulated by selecting the filtered schedule option and entering the regression coefficients to specify the schedule instead of the actual EMC and temperature values.

3.2.3 Test Results for Drying Test 4

3.2.3.1 Schedule Tracking

During drying test DT-4 the actual air temperature and EMC did not track well with the original optimal schedule prescribed (solid line) so the final quality of the lumber is not representative of the capability of a computer optimized schedule. To illustrate this problem, measured air temperature data (circled points) is plotted versus drying time and compared to the initial predicted optimal air temperature schedule (solid curve) in figure
3.2.5A. The measured and predicted EMC is similarly plotted in figure 3.2.5B. The large schedule tracking error caused in part by kiln control problems necessitated a schedule update by midtest. This updated schedule is compared to the measured data in figure 3.2.6.

The following is an attempt to explain the tracking problems encountered in DT-4 and anticipate changes necessary to produce better results in DT-5. The poor tracking of EMC during the period from 0 to 10 days was due to a bias error in the Forest Products Laboratory EMC conversion table used by industry combined with failure of the wet bulb sensors. The standard EMC tables from the Kiln Operator's Manual (Rasmussen (1961)) are based on tests on sitka spruce. As suggested by Wengert (1976), they do not accurately predict the EMC of red oak. In the range from 10 to 20 percent, using EMC sensors of red oak we found the actual value of EMC to be 85 percent of the value estimated from the table. The EMC sensors were thin end grain sections of red oak suspended in wire cages inserted between the courses (layer of boards in the kiln charge). The sensors were used to monitor the drying condition for the remainder of the test. The second EMC tracking problem was caused by progressive degradation of the wet bulb temperature sensor. Although this problem was corrected for the remainder of the test, the drier than specified humidity caused larger than desired initial shell shrinkage strain thus contributing to failure.
Figure 3.2.5

Prescribed (solid line) and measured air temperature and EMC for initial schedule optimization (schedule 1 of table 3.2.1)
Figure 3.2.6

Prescribed (solid line) and measured air temperature and EMC for update performed 30 days into the drying (schedule 3 of table 3.2.1)
The second period of significant deviation from the test schedule was from day 16 through 30. During this period, the dry bulb temperature was too high. The kiln could not be adjusted to hold the prescribed temperature at the prescribed humidity. The minimum temperature that could be maintained by the kiln and still hold the prescribed EMC increased until at 24 days the minimum temperature for the prescribed humidity was 120°F.

The problem of controlling the minimum prescribed kiln air temperature was apparently due to the installation of a steam trap inside the kiln to prevent condensate backup in the spray line during "off" periods. The presence of the trap inside the chamber and its periodic venting into the kiln atmosphere provided a constant source of uncontrolled heat so that the minimum dry bulb temperature could not be maintained. Since steam requirements depend upon the dryness of incoming vent air, ability to control the minimum temperature was also affected by ambient humidity in the air surrounding the kiln.

When this change in low limit temperature control was detected, EMC adjustment was given priority over dry bulb temperature adjustment. When temperature conditions stabilized, a schedule update was performed with the minimum control temperature set at 120°F. This update schedule was optimal for the lumber condition at 32 days and included a minimum dry bulb temperature constraint of 120°F. When the change in minimum temperature occurred,
the original objective of the test, i.e. evaluation of the optimal schedule, had to be abandoned. Nevertheless, response to this event illustrates the controller flexibility. In fact, it would not be possible to write a kiln manual general enough to handle every eventuality that the computer controller is designed to handle.

Obvious problems with the kiln plant such as those described are not necessarily typical problems for an industrial operation. However, as long as industrial dry kilns have varying levels of insulation and draw air from outside, the capacity to control kiln conditions within prescribed limits will be affected by the weather. With a computer controller, whenever weather conditions prevent the actual control within the desired limits a compensating schedule update can be performed.

3.2.3.2 Predicted and Measured Lumber Response

The moisture model prediction for the drying control optimized to the entire set of data from DT-4 is plotted in figure 3.2.7. In contrast to figure 3.2.4, the model optimization for figure 3.2.7 used data from the entire test to produce the drying coefficients. The filtered schedule option was used to produce figure 3.2.7 so that the measured EMC values are represented by a fifth order time polynomial instead of the step interpolation used for figure 3.2.4. The initial rapid drop of measured core moisture from 90 percent to 80 percent is difficult
Figure 3.2.7

Prediction (solid line) and measurements of shell and core moisture content for DT-4
Legend

- Shell
- Core

Moisture Content

Time (Days)

H.C. vs Time (DT4)
to explain. If water is removed across the grain then the drop of core moisture should be delayed from the shell response as illustrated by the model prediction (solid line). Since the initial moisture sample was taken only 3 inches from an exposed end, it is likely that end absorption during the period of water storage (approximately 16 weeks) biased the initial condition measurements. This bias would account for the sudden apparent drop in core moisture because subsequent samples came from the interior which was unaffected by end absorption.

The measured release or elastic strain is plotted in figure 3.2.8 along with the prediction (solid line). The plotted points represent average shell and core strain for the 12 boards sampled. Since tension failures eliminated 5 of the 12 boards by mid test, a representative average could not be calculated. Thus no data is shown after 40 days. Originally, the prediction and therefore the schedule was generated using a shrinkage threshold of 30 percent. Using a 30 percent threshold is equivalent to assuming that there is negligible edge drying. The character of the prediction error was similar in pattern to that of figure 2.2.3.13 suggesting that the actual shrinkage threshold is higher. A threshold of 45 percent based on fitting the prediction to the more reliable prong deflection data in figure 3.2.9 was used to generate the prediction for figure 3.2.8. Since a significant amount of edge drying did occur in DT-4 test boards, a shrinkage
Figure 3.2.8

Prediction (solid line) and measurements of shell and core release strain for DT-4
Legend

○ Shell
× Core

STRAIN VS TIME (DT4)
Figure 3.2.9

Prediction (solid line) and measurements of average shell prong deflection for DT-4 radial boards
Legend

○ Shell

DEFLECTION VS TIME (DT4)
threshold greater than 30 percent was needed. The threshold is less than the 60 percent value used to predict release strain from McMillen because only one of the edges was exposed in the DT-4 test.

Although the time relationship of prediction and data appears to be close, the magnitude of the release strain as shown in figure 3.2.8 is always less than predicted. This is because the actual elastic stress is relieved by viscous creep and by failures (checking). As mentioned in section 2.2.3.4, the viscous strain element of the model was eliminated to get a more realistic estimate of post reversal stress. The stress relief due to failure simply cannot be accounted for by a continuum model.

Prong deflection is a measurement that is more sensitive to changes in the strain gradient than the difference between average release strain for neighboring slices. Shell prong deflection for DT-4 is plotted in figure 3.2.9 along with the model prediction. The deflection measurement plotted is the average shell deflection for radial boards only because this is the only ring orientation for which differences between radial and tangential shrinkage do not influence the prong deflection and thus bias the measurement. In radial boards, the deflection is determined only by the stress gradient within each slice. Since no surface checking occurred to relieve stress in the radial boards, the predicted and measured deflection
agree more closely (figure 3.2.9) than to the results (release strain) for all boards plotted in figure 3.2.8.

If only the subset of the radial boards is used, the sample is biased because the surface fibers of a radial board shrink less than the surface fibers of a tangential board. Under the same drying conditions, this smaller radial shrinkage produces less plastic deformation in the shell of radial boards. The consequence of this smaller initial plastic deformation is delayed stress reversal. Therefore the time of stress reversal for radial boards should occur later than it does for tangential boards. Observation of release strain data board by board tends to support this hypothesis. Since a shrinkage threshold of 45 percent adequately predicts stress reversal for the radial sample boards, the threshold to predict reversal for the average would be between 45 and 60 percent. Although no data exists to positively establish a threshold for average boards, experience would suggest that a 50 percent threshold would more adequately predict the average response. To predict the average stress for the in-pile boards that have no edge exposure a threshold lower than 50 percent should be used. Therefore, 45 percent should be used in DT-5 to predict average in-pile response of edge-planed red oak boards 2 by 5\(\frac{1}{2}\) inches.

It can be concluded that of the two mechanical measurements, average slice strain and prong deflection, the deflection measurement is the most sensitive, reliable
and simple to measure. Prong deflection can be quantified by measuring the change in distance between block corners with an engineering scale (see figure 3.2.2) but release strain requires a dial gage and special precautions during handling. Consequently the industry has always used the sign of the prong deflection for control purposes instead of the release strain.

The data for cumulative failure plotted in figure 3.2.10 represents the percentage of the 12 sample boards that experienced serious failure. Serious failure is defined as a tension failure (check) which splits a shell or core slice. The failure prediction is based on a simulation of a fifth order time polynomial approximation to EMC and temperature. To simulate actual schedule conditions a uniformly distributed control noise of ±2 percent EMC and ±2°F was added to the filtered input schedule values. The failure prediction and the measured data differ during the first 10 days and again after 42 days, the post stress reversal period. The disagreement for the period 0 to 10 days is because the low limit maximum tensile work should be a positive value instead of zero. A lower work limit threshold of zero was used to get the proper slope for the linear type of failure model (figure 2.2.3.9). This suggests that the linear model may be too simplified to predict a low level failure rate and should be reexamined during future research.

Failure after 42 days is due to internal checking
Figure 3.2.10

Prediction (solid line) and measurements of cumulative failure for DT-4
FAILURE (PERCENT/100) VS TIME (DT4 WORK LIMIT MODEL)
or honeycombing. The failures occurred in one board with oblique ring orientation and three of the four boards with radial ring orientation. In each case, the wood failed at 90 degrees to the stress direction predicted by the model. Since the strain model prediction is only one dimensional (x direction stress), no selection of model parameters could account for failure in the orthogonal direction. If in future tests the failure can be more successfully limited, this blind spot of the failure model should not be a problem because honeycombing is frequently associated with high surface checking failures which is adequately predicted by the work limit model. The failure model was also compared to DT-3 failure data as illustrated in figure 3.2.11. The same comments apply to the DT-3 failure prediction as to the DT-4 failure.

Summary

Originally, DT-3 and DT-4 were designed to compare the industry standard drying strategy to the computer approach to drying control on matched lumber samples. That objective was lost when a kiln modification prior to DT-4 raised the minimum control limit for temperature to an unusually high level. The results of the test are still valuable as the adaptability of the controller to this kiln change and to the change in drying characteristics caused by storage degradation demonstrates the worth of the design.
Figure 3.2.11

Prediction (solid line) and measurements of cumulative failure for DT-3
FAILURE (PERCENT/100) VS TIME (DAYS, WORK LIMIT MODEL)
DT-4 serves as the first operational demonstration of all the control procedures. All schedules produced by the schedule optimization, the first procedure, generally agreed within a few degrees of temperature or percent EMC. This consistency of answers from several independent random starts lends confidence that the schedule is a global optimum that is the best of all schedules for the specified performance index. The original schedule used was significantly different from a smoothed version of the present industrial standard schedule in that the starting EMC and temperature for the initial computer schedule were higher. This starting condition might be considered as an extended version of an initial presteaming treatment suggested by some operators as a better way to begin the drying. Holding the EMC at a high value for such a large portion of the DT-4 schedule is also a significantly different feature of the optimized control solution. This may be the computer trying to minimize the stress gradient prior to stress reversal. The initial schedule generated for DT-5 may have a lower initial temperature and a high EMC for a shorter time since the more realistic shrinkage threshold of 45 percent will be used rather than the 30 percent used for DT-4.

A very significant result of the test was verification of the fact that the EMC model used by industry results in a bias error for the estimate of red oak EMC. Actual moisture content at the lumber plant boundary must
be known for computer control, so an unbiased EMC estimate is required. To get such an estimate during DT-4, the desired EMC was first divided by .85 (above 10 percent EMC) before entering the standard EMC charts to obtain temperature and wet bulb depression conversion charts. The modified EMC model should be verified and refined under controlled conditions prior to DT-5.

The most significant result of DT-4 is demonstration of the power of an effective feedback controller to make simple models predict complex phenomena. This means that an effective controller can be designed using simple approximations of the present level of understanding of the drying phenomena. This first real test was a very encouraging start for the engineering effort toward a completely automatic control for drying.
4. SUMMARY AND CONCLUSIONS

With the present rate of computer technology development, process control theory and computational approaches to solving complex problems, a completely automatic optimal control of lumber drying is certain to occur in the near future. The following are conclusions based on the first prototype design of that automatic control mechanism.

4.1 General

1. The qualified success of the first test of a computer generated schedule (section 3.2) establishes the automatic controller design as a workable solution for the process control of hardwood lumber drying. For the first time, an economically optimal schedule for drying lumber was generated entirely by computer. This schedule was followed and later modified in process to account for changes in the control system. Within the limitations of physical measurements of the drying lumber, the test simulation output agreed well with the experimental data. This is the first demonstration of an adaptive closed loop optimal control system for lumber drying.

2. As illustrated by the improvement in prediction
created by exercising the schedule update capability, this adaptive aspect of the controller is responsible for its success. That is, by feedback of only moisture content information, the complete set of moisture and stress states can be estimated with sufficient accuracy to improve upon the original schedule.

3. The controller is also designed to improve the initial drying prediction using information gathered from previous drying runs of the same thickness and species. This additional adaptive aspect is discussed in Appendix A.3.

4. Using a standard industrial dry kiln, a general purpose computer, the program developed through this research and basic statistics, an operator can optimally control the drying process. This implies that after further test verification this program could be implemented by industry for automatic lumber drying control if the computer time required by the present design can be reduced.

5. The schedule used in DT-4 is not a true optimum for 8/4 red oak because the shrinkage threshold (30 percent) used to derive the schedule was too low. Evaluation of results of DT-4 demonstrate that if a threshold of 45 percent had been used, a schedule closer to optimum would have been generated. This higher shrinkage threshold is included with the recommended model parameters listed in table A.6.1.

6. Differences in kiln construction as well as ambient conditions affect the upper and lower limits for
the EMC and temperature control inputs. The controlling program is easily adapted to differences in the control limits by changing the appropriate values in the computer's memory (see RW(17) through RW(20) in the documentation section of the program listing in Appendix A.6).

7. The controller design can be applied with only minor change to any species of hardwood of any thickness using any type of industrial kiln. Only average initial moisture content and the schedule from a previous drying run are needed to determine the moisture model coefficients. Elastic constants, failure limits and differences in shrinkage for the particular species are all that is needed to determine the stress model.
4.2 Optimization Algorithm

8. The function approach to optimization permits unlimited modification in the model without affecting the design of the optimization algorithm. This alternative to the classical variational approach to dynamic system optimization facilitated the development of the optimal control design.

The function (Direct Search) approach (Simplex Method) to optimization was possible only because a Lagrange interpolation definition of the input was used. This approach to optimization has wide potential for process control problems where there is necessity to include only portions of the model. The model may be added to or reduced in complexity without changing the equations used to perform the search. Furthermore, the model is not restricted to an ordinary differential equation form as it is with the classical variational approach.

9. When using the work limit criteria and a different set of initial schedules for each optimization search, results were usually consistent to within the control accuracy of the kiln. Consistency among resulting schedules and with the industry standard schedule suggest that the optimized schedules are all close to the true
global optimum schedule.

10. As presently designed, the control algorithm uses too much computer time (an estimated $4,000 per drying run on the UNH DEC 10 system) to be economical enough for industrial application without significant revision. Therefore this form of the controller must be considered a prototype to a more efficient design perhaps using the gradient search algorithm discussed in Appendix A.5. This variational approach will require that the model be simplified even further.
4.3 Moisture Prediction Model

11. A significant bias error was detected in the equilibrium moisture content model used by industry for drying red oak. Precise control of surface wetness is necessary to avoid surface checking failures. Therefore until an unbiased model is developed, EMC sensors will be needed.

12. A simple one dimensional finite difference model is sufficient to predict average slice moisture content when reliable average moisture content estimates are available. This model is considerably more computationally economical than predictive models suggested by Couture (1969) and Wengert (1976).

13. The moisture model diffusion coefficient equivalent \( G \) can be predicted within the limits required for control using only an algebraic polynomial model with temperature as the independent variable.

14. Until a causal relationship can be established between the control variables (EMC and temperature) and the population variance, the automatic control will not realize its full potential for the quality control phase of drying phase two; equalization and conditioning. However, there are indications that the population variation can be modeled as a skewed normal distribution with constant variance from
green to 12% moisture content.

15. The moisture model and the model optimization procedure which together form a moisture estimating system can be used to get an accurate estimate of core moisture content when only the average moisture content and EMC time history are known. This means that a computer, a computer program and a load cell monitoring the lumber weight loss could be used to advantage for drying control. Development of this system would probably produce the most significant practical application of this research in the near future.
4.4 Stress Prediction Model

16. The stress model, a combination of a hysteresis and a modified Maxwell model is the first drying model that accounts for plastic and viscous behavior simultaneously.

17. Based on the agreement between simulation and data, the simple hysteresis model in the controller defined by linear interpolation of the elastic stress, failure stress and strain limits is a sufficiently faithful approximation of the actual instantaneous stress-strain relationship for purposes of control.

18. As a result of a modification of the incremental approach to the hysteresis model the elastic properties were allowed to depend on moisture and temperature.

19. The viscous model was excluded from the final analysis as it caused the post reversal stress to be too small. The functional dependence of the viscous coefficient on both wood moisture and temperature was established with too few (4) independent test condition. When more test data is available this model may be redeveloped and reevaluated. Due to the compatibility condition used, this exclusion has the effect of causing the initial stress to be overestimated and thus the model makes an overestimate of failure for the beginning of the schedule. This will cause the answer to be more conservative for the
beginning of drying and less conservative for the end. Since surface failure is most likely during the initial period of drying, this is the best design choice for the controller until a significant improvement is made in the model predictive ability.

20. The model prediction for failure based on the work limit criteria suggested by Byvshyk (1960) is better than a maximum stress condition for the situation tested.

21. The failure prediction model is not able to predict honeycomb failures of radial boards. This type of failure depends on a stress component orthogonal to the stress represented by the model. This will not be a practical problem as honeycombing occurs only for schedules much more severe than the true optimum.

22. As a result of using the model for analysis, an experimental result inconsistent with elastic-plastic memory theory was detected (see figure 2.2.3.18). Either the mechanism for increase of set strain is not simply elastic-plastic or experimental error is at fault. If future developments suggest a reexamination of the stress-strain relationship is necessary, this question may then need to be answered by additional experiments.
4.5 Economic Model

23. The objectives (energy, time and final lumber quality) of hardwood drying can be used to define a quantitative model for calculating the model drying cost. Furthermore the model is designed so that an operator may easily determine the coefficients by using the computer and measurements now routinely made.
4.6 Strain Measurements

24. Release strain measurement of slices using a dial gage is impractical for industrial use. The strain estimate, a small difference of two large numbers, is sensitive to deflection distortion of the slice, moisture loss and temperature drop during measurement.

25. The prong test now used by industry is more sensitive to stress gradients and less subject to errors caused by drying and temperature change during measurement. The test could be easily quantified by use of a caliper or scale for measuring the change in distance between corners of the block due to cutting the prongs. If the equipment is available, the photocopier referred to in section 3.2 may be used to advantage. The prong test is only an unbiased measurement if radial boards are used. This in effect biases the estimate of average prong deflection as only the most slowly drying boards with the smallest shrinkage gradient are considered. This bias can be compensated for by developing a model to predict only for the radial boards in the population. If desired, the mechanical model coefficients can be optimized based on the prong test in the same way that the moisture model is now optimized based on estimates of average moisture content.
Summary

The controller design represents a significant change in sophistication from the present operator controlled set point schedule to an optimal controller where the feedback loop is closed through a computer. Implementation of the system might be made as three individual steps; 1. an operator programmable microprocessor controller designed to smoothly change the EMC and temperature as a function of either time or average moisture content (weight of the charge), 2. the microprocessor system with the moisture estimating system referred to in conclusion number 15, 3. an advanced microprocessor controller based on a simpler model and improved optimization algorithm that will perform all the functions necessary for completely automatic optimal control. Implementation of a more sophisticated control will result in savings of three very important resources: 1. time, 2. energy and 3. lumber.

This study demonstrates that with feedback available completely automatic control is now possible. The computer technology is sufficiently well developed, and as has been demonstrated, the models exist to do the job. With the optimal feedback controller as a framework, research can be directed toward a more efficient lumber drying controller.
5. RECOMMENDATIONS

In the near future, a lumber dry kiln will be automatically controlled by computer. At first two computers will be required. A small computer, possibly microprocessor based, at the kiln site will replace the present set point controller performing the remote sensing task automatically and a large time shared computer will be required for the operator to perform the more involved procedures such as schedule update. Eventually, all the control functions will be handled at the kiln site. The following recommendations are provided as an aid to extending the present developmental work toward realization of an optimum controller design.

Development of the advanced automatic optimal controller referred to as step 3 in the summary of section 4.0 can be accomplished as a coordinated result of two separate efforts. The first effort should develop the kiln control hardware. The second effort should develop the theoretical models. The microprocessor controller that would evolve as step 1 of the first effort in no way depends on any development of this study. Once developed, the microprocessor could be immediately used by industry to improve the operation of conventional equipment. For example, conventional equipment could be
modified to dry lumber better than existing equipment at lower cost. Therefore, the microprocessor controller would be a marketable device. If provision were made in the original microprocessor design, the moisture estimating system referred to as conclusion 17 could be implemented producing a more sophisticated system than is available today thus completing the design of the advanced automatic controller (Step 2 in the summary of section 4.0).

The second effort may be a simultaneous development of the models. Based on the results of this study and further tests, the models can be simplified and combined with a more efficient search algorithm to form the basis for the completely automatic optimal lumber drying controller.

5.1 Advanced Automatic Controller

Since rapid changes in drying air humidity and temperature cause high peak stress, it is widely accepted that a smoothly varying schedule is better for drying lumber. Until recently, only set point controllers designed for step schedules were available. The Hildebrand (1977) company offers an automatically controlled kiln which can produce a smoothly varying schedule based on lumber moisture. This option is expensive and cannot offer the flexibility of a microprocessor system. In addition to making the humidity and temperature transition effectively continuous, the microprocessor system could be programmed to:

1. Accept and run a schedule as a smooth interpolation of
specified temperature and EMC values entered by the operator. 2. Run the schedule automatically and shut down the kiln when target moisture content is reached. 3. Detect humidity sensing equipment failure and switch to a backup system or shut down the kiln if necessary. 4. Update the estimate of the limits of EMC and temperature control by using sensors on the intake vents. If the requested control inputs from the computer program are outside the control limits of the kiln then the operator should be alerted. 5. Insure that the humidity is maintained while the temperature is being changed. It is very likely that in certain situations the operator may wish to run a stepped schedule with the controller. When increasing the temperature, it is important that the EMC does not go below the value specified for the next step.

A controller designed to perform these tasks could have been of much help during DT-4. The continuously variable optimal schedule was approximated as a stepped schedule where the conditions were changed once per day. This adjustment was difficult and time consuming. As discussed in section 3.2, sensor failure and uncertainty of the control input limits also caused problems. The wetbulb depression sensor dried out during DT-4 causing a drastic reduction in humidity producing wood failure before the problem was detected by the operator. Therefore the following recommendations are made:

1. Design and implement a microprocessor controller
to accomplish the functions outlined above.

2. Make provision in the controller design so that it may be expanded to incorporate the core moisture estimation feature discussed in conclusion 17.
5.2 Automatic Optimal Controller

Tests and modifications will be necessary before the present design is streamlined enough for the industrial version of the optimal controller. A minimum of two tests will be necessary to experimentally establish the drying cost, one for the standard schedule and one for the optimal schedule.

There are a number of improvements that can be made prior to the tests thus greatly increasing the value of the information gained:

5.2.1 Improvements to the Moisture Prediction Model

3. Uncertainty in control of lumber surface humidity during DT-4 was due to the inadequacy of the industrial standard EMC predictor model for red oak. At some conditions, a bias error of up to 15% of the control value was detected. Weighing very short endgrain samples involves too great a time delay to be a practical procedure for checking on kiln adjustments. Therefore, an unbiased EMC predictor model is needed so that control may be accurately based on the air temperature and humidity.

4. The most critical drying cost associated with hardwood drying is due to surface checking. The prediction
of surface checking depends most on the moisture gradient near the surface of the control volume (lumber). As explained in section 2.2.2.2, an exponential model was used to predict the moisture content at the control surface. To improve this prediction, the effect of air velocity on the surface drying time constant should be determined.

5. To use the control for equalizing the conditioning, the studies by Fell (1978) must be extended to determine the dependence of the population variance for moisture content and stress on the humidity and temperature control inputs. A text by Schweppe (1973) contains a good discussion of variability in dynamic systems.

6. As discussed in Appendix A.3, the drying coefficient data base for the drying prediction model is expanded by the operator after each drying run. Before industrial implementation of the system, this procedure for update of the data base (table A.3.1) should be completely automated. Also further research on this subject should include modifying the model so that the effect of moisture concentration on the drying coefficient (see equation 2.2.2.7) can be considered.

5.2.2 Improvements to the Stress Prediction Model

7. The moisture and stress prediction models used in this study are very simple one dimensional approximations to the actual three dimensional situation. If a two dimensional model could be made computationally efficient, then
the failure prediction could be based on the peak stress across the board width which causes the failure rather than the average stress as it is now. It is possible that even if a two dimensional model cannot be simplified, a better one dimensional model may be developed as a result of studies with the two dimensional model. The two dimensional model could also serve as a tool for quantitative analysis of photoelastic data. The two dimensional analysis is a difficult problem even if an isotropic approximation is used. It may be more practical to use an available program designed to perform a finite element analysis.

8. The test information used to determine the dependence of the viscous coefficient on moisture and temperature is inadequate (section 2.2.3.4). If tests show that the stress prediction using the elastic-plastic component alone is not sufficiently accurate, then further creep testing will be required.

9. Conclusion 22 raises the question of whether experimental error or an inadequate understanding of the stress-strain relationship explains the disagreement of predicted and observed set strain (see figure 2.2.3.18). Since the stress-strain model is such a very important element of the drying controller, this question should be resolved with further experimentation.

10. Stress based on an isotropic model is too low to account for observed failure (section 2.2.3.2). To account for the effect of asymmetry of shrinkage on stress,
a bias stress model was developed. A more sophisticated analysis of the effect of shrinkage asymmetry on displacement by Hsu and Tang (1975) may provide a basis for improvement of the model.

5.2.3 Improvements to the Economic Model

11. Since implementing the changes suggested should alter the estimated physical costs for a standard schedule, the cost coefficients will need to be recalculated. In order to establish the physical costs, the standard drying schedule must be simulated. In practice, the change in EMC and air temperature is specified for the average of the wettest half of the charge but the simulation is based on an unbiased average. For practical purposes, to simulate the wettest half, it is sufficient to subtract 4 percent moisture content from each step in the schedule before running the simulation.

5.2.4 Improvements to the Optimization Algorithm

12. During the optimization searches for DT-4, the trial EMC and temperature schedules were Lagrange interpolations of values specified at 0, 20, 40, 60 and 80 days. This limited the most rapid EMC or temperature transition that could be represented to a ramp function of EMC or temperature with time over a 20 day interval. This is roughly equivalent to the schedule possessing a maximum frequency component of one sinusoidal cycle every 80 days.
or about $1.45 \times 10^{-6}$ Hz. The schedule that results from the subspace search may be a better approximation of the true optimum if the times at the specified points (temperature and EMC) are more closely spaced when a rapid transition is required. For example, if a rapid change in EMC is indicated between 20 and 40 days then the subspace search might produce a lower final cost if the elapsed times for each specified schedule point were 0, 20, 30, 40, and 60 days.

Another criteria for changing the spacing of the schedule points is based on the output of the schedule sensitivity analysis procedure. For example, if perturbation of the EMC value at 20 days produced the greatest change in the drying cost then this is the most critical time for the EMC specification. The pivotal schedule for the focused search procedure described in Appendix A.6 might then be chosen to be 0, 15, 25, 40, and 60 days. Such weighted spacing may result in an improved final solution.

13. Application of the principles of the calculus of variations will produce most significant improvement in the optimization algorithm. This redesign of the search algorithm is discussed in Appendix A.5.

5.2.5 Improvements to Measurement Techniques

14. With present technology, moisture content is the only lumber variable which can be economically measured for purposes of an industrial drying control. The oven tests used for DT-4 are too time consuming and involve too
much delay for most drying situations. A remote sensing scheme is needed to provide input for a microprocessor controller. For example, a) a displacement sensor such as a linear voltage displacement transformer (LVDT) to detect changes in the across the grain dimension of a thin endgrain section of wood might provide a very sensitive indication of air humidity changes and therefore wetness at the lumber surface. Since shrinkage for a very thin section (no gradients), is linear with moisture content, the calibration of such a sensor is straightforward. b) Some systems presently sense core moisture from conductivity measurements. Automatically multiplexing these measurements into the microprocessor is relatively straightforward but there have been difficulties associated with the electrodes that cause the readings to drift with time. Furthermore, this method is only practical for the drier portion of the drying cycle. By using an alternating current through the electrodes most of the drift problem should be alleviated. c) Another scheme for sensing core moisture is to use thermocouples at the wood surface and imbedded in the wood. Change in surface temperature causes a delayed change in core temperature. The delay is a function of the thermal conductivity which in turn depends on the wetness. Optimizing the model to the temperature data will provide an estimate of thermal conductivity which can be used to estimate the wetness. The thermal conductivity scheme has the advantage that it is more fundamental and will not be affected by variability.
in ionic concentration as are the conductivity measurements. The disadvantage is that this approach requires a great deal of computational effort. A very simple approach to moisture sensing is an instrumented version of the sample board weight technique now used. Instead of weighing a few boards, a large portion of the load is weighed by a remote sensor called a load cell. If a representative sample of the load is initially tested for moisture using the oven test, then the load cell reading can be used to indicate average moisture content for the load. Using a microprocessor for control, the humidity and temperature conditions can be set according to the load cell reading. These four methods should be thoroughly investigated prior to the final controller design.

15. Since regulation of the strain state of the lumber is also a control objective, a future version of the controller might be designed to utilize sensed strain in the feedback loop to determine the control. Ugolev (1976) has tested a device to measure change in distance between separate points on a board which might be adapted for control purposes. His approach should also be evaluated and tested.

16. Development of a two dimensional model was suggested in recommendation number 6 for purposes of analyzing strain measured by photoelastic coatings. If peak surface strain is highly correlated to average release strain as measured by the slice and dial gage approach then a simpler
model for control purposes might be developed based on the one dimensional model now used. To gather data for this purpose, a small strain gage or thin photoelastic strip applied at the point where peak strain will occur will provide the data necessary for this model development.

17. Future tests may indicate the need for a refinement of the failure prediction model. The results presented in section 3.2 suggest that a non-linear relationship may be required to adequately predict low failure rates. If this is necessary, refined measurements may be needed. A simple but effective technique for establishing a composite picture of the failure distribution was demonstrated by Leney (1964). This simple technique could be applied in future tests to establish that distribution.

5.2.6 Drying Cost Evaluation Tests

It is important that benchmark drying costs be established for the industry standard schedule and the optimal controller in order that the advantage of the optimal controller be quantified. If the reduction in drying cost traceable to the optimal controller does not more than offset the computational cost then the controller should not be used. In that case a cost effective suboptimal controller may be a better answer.

18. For proper cost comparison purposes, the standard schedule according to Rasmussen (1961) should be run at low air velocity (less than 300 feet per minute)
with step changes based on the average moisture content of the wettest sample board. Time and heat costs can be evaluated by using the coefficients from section 2.3. A random sample of final moisture content is all that is needed to evaluate the phase 1 portion of this schedule although periodic sampling would provide valuable information for model development. The stress and strain costs will have to be estimated using the model but periodic measurement of prong deflection can provide data to be used to verify the accuracy of this prediction. As suggested in recommendation 15, failure should be measured according to Leney's (1964) technique. This will involve periodic application of dye followed by cross cutting and measuring the depth of the dye marks at the end of the drying run.

19. For the two tests to be comparable, the test of the optimal controller should be run using the same air velocity (300 fpm) as suggested in 16. The three performance categories (heat, time and final quality) must be evaluated in the same manner so that the same physical measurements must also be made. In addition, the control procedures discussed in section 3.2 and A.6 must be followed. A composite drying model coefficient will need to be determined using the information in A.3. When conducting a schedule or model optimization, use the RW and IW vector values suggested in A.6 for file WDOPT.DAT. There is a "warming through" option which has been added to the controller since DT-4. This "warming through" option
provides for a gradual warmup in the drying schedule so that stresses due to thermal gradients might be avoided.

To use this option with a period of one day set RW(141)=1.0.

Summary

The lumber dry kiln controller of the near future will be a small unit with a keyboard for the operator to enter instructions. The operator will key in a schedule which results from an optimization performed on a larger time shared computer. This controller will then regulate the temperature and humidity in accordance with the schedule until the end of phase one is reached or a comparison of measured and predicted lumber states indicates a discrepancy. When this discrepancy occurs, the operator is alerted and can obtain an updated schedule from the main computer. The design of the prototype program for the main computer was the subject of this thesis. The recommendations are intended to suggest improvements in the prototype program or control optimization procedures to permit economical implementation in a computer controlled lumber drying scheme.
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Appendix 1: An Electrical Lumber Drying Model Analog

An electrical analog model was found to be a powerful analytical tool to visualize interrelationships and to borrow circuit techniques for writing equations used in the drying model. A lumber drying analog model is presented because of its potential for future model development. Also the analog electrical circuit can be used as part of a larger circuit which could act as an inexpensive analog computer for training kiln operators. This training tool could prevent losses in lumber and time due to operator inexperience with the present trial and error process.

Electrical voltages and currents in the analog circuit simulating moisture transport have a different physical meaning than they do in the analog circuit simulating stress development. The moisture analog drives the mechanical analog circuit just as shrinkage gradients generate stress gradients in drying wood. Therefore the moisture transport and stress models will be discussed separately. Simulation events will be related to physical events in section A.1.3. The complete design of the analog kiln computer is too involved to present here but some of the more important facets of the design are discussed
A.1.1 Moisture Transport Analog

As explained in section 2.2.2 moisture transport in lumber can be modeled by a one dimensional diffusion model

\[
\frac{\partial M}{\partial t} = \frac{\partial}{\partial Y} \left( D \frac{\partial M}{\partial Y} \right)
\]

(A.1.1)

\( M \) = moisture content
\( t \) = time
\( D \) = diffusion coefficient
\( Y \) = thickness coordinate of the board

The variation of D with Y is influenced by differences in the wood structure related to the presence of heartwood and sapwood in the same board. Since ray cells conduct moisture easily, diffusion is also influenced by the angle (a function of Y) that the rays (tree's radial axis) make with the board's Y axis. For example, along the centerline of a flatsawn board the Y axis of the board is aligned with the tree's radial (R) axis. Along the centerline of a quartersawn board the Y axis is orthogonal to the R axis. Assuming that there is no systematic variation with Y of the distribution of heartwood, sapwood and growth ring angle within the boards which make up
a typical charge, $D$ can be modeled as independent of $Y$. If $D$ is independent of $Y$, then

$$\frac{\partial M}{\partial t} = D \frac{\partial^2 M}{\partial Y^2}$$

(A.1.2)

If the finite difference approximation is substituted for the second derivative and the first partial derivative is expressed as a total derivative then the model can be written as

$$\frac{dM_{i,j}}{dt} = \frac{D}{\Delta Y^2} \left( M_{i,j-1} - 2M_{i,j} + M_{i,j+1} \right)$$

(A.1.3)

which as Chapman (1967) points out is in the form of a node equation for a simple RC circuit of the type shown in figure A.1.1. The model presented in this figure is a three level version of the six level model actually used. The voltage source represents moisture content at the lumber plant boundary as expressed by (2.2.2.6). The analogy is complete when (A.1.3) is multiplied through by the volume

$$V_j = A_j \Delta Y_j$$

(A.1.4)
Figure A.1.1

Electrical resistor-capacitor ladder circuit analog for moisture transport in the drying board
Capacitor voltage = moisture content
Voltage source = surface wetness
\[ V_j = \text{volume} \]
\[ A_j = \text{area} \]

so that (A.1.3) can be expressed in exactly the form of Kirchoff's current law

\[
V_j \frac{dM_{i,j}}{dt} = \frac{DA_{j,i}}{\Delta Y_j} \left( M_{i,j-1} - M_{i,j} \right) + \frac{DA_{j,i}}{\Delta Y_j} \left( M_{i,j+1} - M_{i,j} \right)
\]

(A.1.5)

where \( \frac{DA_{j,i}}{\Delta Y_j} \) is like the conductance of the resistors \( G_j \) and \( V_j \), the volume is analogous to capacitance. The general form of the Kirchoff's current law equation for the \( j^{th} \) node of the circuit illustrated in figure A.1.1 is

\[
C_j \frac{dv_j}{dt} = G_j \left( v_{j-1} - v_j \right) + G_{j+1} \left( v_{j+1} - v_j \right)
\]

(A.1.6)

\[ v_j = \text{capacitor voltage at the } j^{th} \text{ node} \]
\[ C_j = \text{capacitance of the } j^{th} \text{ node} \]
\[ G_j = \text{conductance connecting nodes } j \text{ and } j+1 \]

If each node represents equally spaced locations in the board then each volume is the same and \( C_j \) the equivalent capacitance can be normalized to one. If the forward
difference approximation is substituted for the time derivative then the model can be expressed as

\[ \frac{M_{i+1,j} - M_{i,j}}{\Delta t} = G_j \left( M_{i,j-1} - M_{i,j} \right) + G_{j+1} \left( M_{i,j+1} - M_{i,j} \right) \]

(A.1.7)

which can be expressed in the form of (2.2.5) repeated here for convenience.

\[ M_{i+1,j} = \Delta t G_j M_{i,j-1} + \left( 1 - \Delta t (G_j + G_{j+1}) \right) M_{i,j} + \Delta t G_{j+1} M_{i,j+1} \]

(A.1.8)

If the diffusion coefficient, represented by \( G \) in (A.1.7) is a function of the moisture content, then \( G_j \) is not equal to \( G_{j+1} \). If the node spacing is not equal as is the case in figure A.1.1 then \( C_j \) must also be retained.

The three level model in figure A.1.1 is suggested because it is used for the discussion in Appendix A.5 of a simpler model for use in a microprocessor controller.

A.1.2 Stress Analog

The Maxwell stress-strain model can also be represented by a simple series resistor and capacitor circuit branch element. An analog circuit representing a drying board is shown in figure A.1.2. The voltage sources in
Figure A.1.2

Electrical analog circuit for shell-core Maxwell viscoelastic model
Resistor voltage = elastic strain
Capacitor voltage = viscous memory strain
Current = stress
the stress analog represent unrestrained shrinkage, the shrinkage experienced by the wood when there are no moisture gradients. The interconnection of the resistor-capacitor branch elements represents the restraint to uneven shrinkage caused by the moisture gradient. If current in the branch elements represents stress in the drying board then the voltage across the resistor \( V_g \) in the Ohms law model of the branch resistor represents strain.

\[
I = G \cdot V_g
\]  
(A.1.9)

\( I \) = branch current  
\( G \) = branch conductance  
\( V_g \) = conductance voltage

The resistance (or conductance) is analogous to the elastic component of strain in the Hooke's law model for a spring.

\[
\sigma = E \cdot \varepsilon_{eL}
\]  
(A.1.10)

\( \sigma \) = stress  
\( E \) = Young's modulus of elasticity  
\( \varepsilon_{eL} \) = elastic component of strain
The capacitor voltage \( V_c \) in the circuit is related to the current \( I \) by the equation:

\[
I = C \frac{dV_c}{dt}
\]  

(A.1.11)

\( I \) = branch current  
\( C \) = capacitance  
\( V_c \) = capacitor voltage

This equation is mathematically equivalent to the creep strain equation for the Maxwell dashpot equation expressed as:

\[
\sigma = \beta \frac{d\varepsilon_v}{dt}
\]  

(A.1.12)

\( \sigma \) = stress  
\( \beta \) = creep coefficient  
\( \varepsilon_v \) = viscous or creep strain

As the spring stiffness and creep coefficient are dependent upon wood moisture and temperature, the resistor and capacitor values in the analog model depend on the simulation temperature.

A.1.3 Simulated Response

If the voltage in the analog circuit is scaled so
that 10 volts in the moisture circuit corresponds to 100 percent moisture content in red oak then the initial voltage on the capacitors would be 8 volts. The source voltage in the moisture circuit would actually be the voltage of a capacitor with an initial charge of 8 volts connected to a battery representing the air EMC with a maximum voltage of 2.6 volts by a resistor of high conductance value. As time goes to infinity, the capacitor voltages all tend to the EMC battery voltage which is decreased in steps until the EMC voltage is between 1.0 and 0.6 volts.

While the drying is being simulated, capacitor voltages in the moisture model analog are translated into voltage sources for the stress analog model. Source voltage in the stress analog circuit represents unrestrained shrinkage. In the stress model analog, the difference in voltage for the two sources causes a current to flow. This stress circuit current is analogous to the stress due to shrinkage gradients. Capacitor voltages in the stress circuit depicted in figure A.1.2 correspond to the viscous component of strain. Change in these voltages lags variations in the source voltage difference. In the initial stage of drying, the shell and core have a large difference in moisture causing a shrinkage differential between shell and core. This is analogous to a large difference in the voltage source values of the stress analog circuit. As drying proceeds and core wetness approaches shell wetness,
this difference diminishes. Since the decay of the capacitor voltage in the stress model lags the decay of the source difference, the current in the loop may reverse. This current reversal is analogous to stress reversal in the physical situation.

A.1.4 Analog Computer

In order to make a complete analog computer simulation, one circuit would have to be developed from the two circuits presented. A coupling, which is analogous to the transformation of moisture into shrinkage strain, could be accomplished with an operational amplifier circuit.

Only the viscous memory element used in the computer controller simulation model is included in the analog circuit model. With proper selection of the model coefficients, the viscous model analog simulation can be made to agree fairly close to observed behavior of the release strain measurement. If a simulation with this model is not sufficiently accurate then the other hysteresis memory component discussed in A.3 can also be modeled with operational amplifiers, diodes, resistors and capacitors. An example of a circuit that can be constructed to simulate a hysteresis memory can be found in the documentation for the TR48 analog computer (1966).

The EMC battery voltage and the moisture model circuit resistors are analogous to the control inputs of air humidity and temperature respectively. The heat loss
model is simulated by using the resistor control corresponding to temperature to control a voltage which is integrated by a standard integrator circuit. The time component of the drying objective function or performance index is simulated with a constant voltage and an integrator circuit. Assessing the final moisture content, residual stress and plastic strain involves sensing the appropriate voltage with an operational amplifier. Failure modeling using maximum stress or strain criteria involves sensing the appropriate voltage or current with a peak detecting amplifier and applying the resulting signal to a differential amplifier. The alternate input to the differential amplifier represents the maximum value for either stress or strain. Since the work limit criteria for failure is analogous to a maximum power dissipation criteria for resistor failure in the stress circuit, failure may be more easily simulated by using resistors with appropriately limited dissipation ratings. Using this simpler circuit has the disadvantage that it does not allow the voltage representing failure for the population to be put into a summing amplifier with the other voltages which represent the other components of the cost of drying.

The objective of having the operator train with the analog computer is to vary the EMC voltage and resistors that correspond to the temperature control to achieve the lowest value for the voltage that corresponds to the cost of drying.
Summary

In addition to facilitating development of the original model, the electrical analog concepts of capacitance representing volume and conductance being inversely proportional to node spacing simplifies development of a more sophisticated model if research indicates that uneven spacing of the nodes is of advantage. A mechanical analog model could have served this model development purpose as well but the electrical analog more readily brings to mind circuit analysis techniques which may be of special value to future analysis. For example, the Laplace transformation technique can be used to derive the analytical solution for the analog moisture and stress models developed in this study. The analytical solution may be of special value to analyzing cyclical variation in the control input such as that occurring in lumber drying with solar kilns.
Appendix 2: Moisture Content Statistics

An optimal computer control algorithm is only as good as the drying model that it uses for moisture prediction. The schedule is optimal not for the lumber being dried but for the model that predicts that drying behavior. The moisture model, the subject of this appendix, must predict the behavior of both the mean and variation of moisture in the lumber population. The model used in the present version of the computer control algorithm is only designed to predict the behavior of the mean. Simplifying assumptions about the variation are substituted for the non-existent variance predictor model. A model for the prediction of moisture variation in a lumber drying distribution has been developed by Fell (1978). One of his results and some accompanying statistics computed by him are presented in section A.2.2. Data for the mean moisture predictor is presented in section A.2.3.

A.2.1 Testing Plan

To date, four drying tests have been run at UNH with the same test objective. That objective is to produce information for the design of a drying model for the
optimal control algorithm. The first test (DT-1) was run according to an extremely accelerated drying schedule. The second test (DT-2) was designed to give maximum information about the effect of the control variables on drying rate. The temperature and EMC were varied every $3\frac{1}{2}$ days. The third test (DT-3) was again an accelerated schedule but was only a moderately accelerated version of the industrial standard schedule for two-inch red oak. The fourth test (DT-4) was run according to the computer schedule. The first two tests were designed to provide data over the entire dynamic range of interest so that a general picture of the red oak drying model could be formed. The third and fourth test were designed to evaluate specific schedules. Fell (1978) provides more detail on the design of all four tests.

A.2.2 Drying Population Statistics

In table A.2.1 (DT-1) the moisture content represents an average of 10 boards taken from five different trees. In DT-1 as in all the tests, the boards sampled were placed on the trailing edge (side where air was exiting the lumber stack) of a small kiln charge (500 board feet or less). The air velocity indicated in tables A.2.3 and A.2.4 was measured with a fan type air flow velocity indicator as the electronic Hastings Air Meter was out of calibration. Since the fan system was upgraded previous to DT-3 and the air velocity for DT-2 appeared
Table A.2.1

Elementary statistics of 10 boards sampled during Drying Test -1 (accelerated schedule)
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1. USING STANDARD EMC CHARTS
2. AIR VELOCITY IN FEET PER MINUTE MEASURED WITH HASTINGS AIR METER MODEL B-22

HASTINGS-RAYDIST INC, HAMPTON VA.
3. STANDARD DEVIATION
Table A.2.2

Elementary statistics of 10 boards sampled during Drying Test - 2 (Control Variable Effectiveness Test)
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1. USING STANDARD EMC CHARTS
2. AIR VELOCITY IN FEET PER MINUTE MEASURED WITH HASTINGS AIR METER MODEL B-22
3. STANDARD DEVIATION
   * KILN CLOSED, FANS OFF DURING KILN SHUTDOWN PERIOD
Table A.2.3

Elementary statistics of 12 boards sampled (only 6 sampled at each time) during Drying Test - 3 (accelerated version of schedule T3D1)
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<td>160</td>
<td>7.9</td>
<td>414</td>
<td>7.7</td>
<td>2.51</td>
<td>7.3</td>
</tr>
<tr>
<td>59</td>
<td>160</td>
<td>7.9</td>
<td>414</td>
<td>8.1</td>
<td>1.01</td>
<td>7.8</td>
</tr>
<tr>
<td>62</td>
<td>160</td>
<td>7.9</td>
<td>414</td>
<td>7.0</td>
<td>2.37</td>
<td>6.3</td>
</tr>
</tbody>
</table>

1. Using Standard EMC Charts
2. Air Velocity in Feet per Minute Measured with Taylor Fan Type Air Meter
3. Standard Deviation
* Missing Data
to be higher than the highest air velocity in DT-3, the
414 Feet Per Minute (FPM) average is a low estimate of
the actual value. The table air velocity listed represents
an average of readings taken at the bottom, middle and top
course of that kiln charge. The air velocity at the top
course of the charge was 50 FPM greater than the average
and the air velocity through the bottom was approximately
50 FPM less for the average of 414. The range is not
available for DT-1 and DT-2. Sample boards were always
located so that both tangential and radial boards were
exposed to both high and low air flow rates. Since two
blocks (one from each end of the board) were taken from
each board in DT-2, a different group of sample boards
were used for the second half of this test. The schedule
for DT-3 is the one (T3D1 Kiln Operator's Manual) normally
used for 8/4 inch red oak. The maximum air velocity
480 FPM was higher than recommended and control was based
on the average moisture content of the sample boards
instead of standard practice which prescribes using the
average of the wettest half of the sample boards. This
deviation from standard procedure resulted in the EMC and
temperature steps being made earlier than intended by the
schedule. In table A.2.4 the schedule EMC and temperature
values represent averages but since the schedule in this
case was continuously varied, a greater range of values
is represented by this average. The individual values
for the DT-4 test are plotted in figure 3.2.5. Experience
Table A.2.4

Elementary statistics of 12 boards sampled during Drying Test - 4 (evaluation of computer controller)
<table>
<thead>
<tr>
<th>TIME</th>
<th>TEMP</th>
<th>EMC(^1)</th>
<th>A.V.(^2)</th>
<th>AVERAGE M.C. (%)</th>
<th>SHELL M.C. (%)</th>
<th>CORR M.C. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAYS</td>
<td>°F</td>
<td>%</td>
<td>F.P.M.</td>
<td>MIN</td>
<td>MEAN</td>
<td>MAX</td>
</tr>
<tr>
<td>0</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>1.5</td>
<td>123</td>
<td>16.2</td>
<td>414</td>
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<td>80.1</td>
<td>90.3</td>
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<td>4.5</td>
<td>127</td>
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<td>414</td>
<td>57.0</td>
<td>62.8</td>
<td>69.3</td>
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<td>44.0</td>
<td>48.9</td>
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<td>116</td>
<td>18.2</td>
<td>414</td>
<td>36.6</td>
<td>40.2</td>
<td>47.3</td>
</tr>
<tr>
<td>29.5</td>
<td>120</td>
<td>16.2</td>
<td>414</td>
<td>31.5</td>
<td>42.2</td>
<td>52.7</td>
</tr>
<tr>
<td>32.5</td>
<td>120</td>
<td>16.2</td>
<td>414</td>
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<td>35.6</td>
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<td>126</td>
<td>12.5</td>
<td>414</td>
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<td>28.7</td>
<td>34.0</td>
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<tr>
<td>46.5</td>
<td>165</td>
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<td>14.8</td>
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<td>24.7</td>
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<tr>
<td>53.5</td>
<td>172</td>
<td>9.5</td>
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<td>67.5</td>
<td>166</td>
<td>7.0</td>
<td>414</td>
<td>4.4</td>
<td>6.7</td>
<td>8.8</td>
</tr>
</tbody>
</table>

1. MEASURED USING THIN END GRAIN SECTIONS OF RED OAK
2. AIR VELOCITY IN FEET PER MINUTE MEASURED WITH TAYLOR FAN TYPE AIR METER
3. STANDARD DEVIATION
gained in DT-4 supported results reported by Wengert (1976) which suggest that for certain conditions, the EMC for red oak is lower than the average EMC for sitka spruce which appears on the EMC conversion charts developed by the Forest Products Lab and used by industry. Since the EMC charts were used for the first three tests, the EMC values listed in the corresponding tables are too high. However, the EMC values listed in table A.2.4 are measured moisture contents of thin endgrain sections of red oak taken from the same air stream as the board surface.

Summary

The detailed conclusions using a broader base of statistical analysis than presented here are discussed by Fell (1978) but some preliminary conclusions can be drawn after examining the elementary statistics in these tables. For example, starting from seven days into drying until the mean reaches about 12 percent, the standard deviation of the core and average board moisture contents can be modeled as a constant. Also during this period, the mean is usually midway between the minimum and maximum values which suggests that the distribution is symmetric. Below 12 percent the mean tends to come closer to the minimum value. As expected because the EMC is being closely approached, the variance in the distribution is decreasing. In other words, the distribution is becoming skewed because the fast drying boards near the EMC wetness have
stopped drying.

As stated in section 2.2.2.1, the data taken and the statistical analysis performed by Fell (1978) is for the purpose of quantitatively describing variation in the lumber population during the pre-equalization portion of the drying cycle. With further development, this model will be refined so that automatic control may be extended to the equalization and conditioning phase of drying.
Appendix 3: Moisture Prediction model Optimization

Suppose a researcher wished to discover if a certain algebraic model could be used to predict some observed phenomenon. If he took coincident measurements of the independent variables and the dependent variable which together form observation vectors, then he could use these vectors and an analysis technique called regression to optimally estimate the coefficients of the hypothesized model. The resulting answer would be model coefficient estimates which when incorporated into the algebraic equation would produce a model that predicts the observations with a minimum mean squared error. If the model hypothesized is a complete description of the physical phenomenon, then as the number of observation vectors included in the regression analysis increases, the uncertainty in the coefficient estimates decreases. The minimum number of points required for regression should exceed the number of degrees of model freedom by at least one. For example, if the model being used for the dependent variable is a cubic polynomial in the independent variable then the model has four degrees of freedom. If only four observation vectors are used, the regression becomes an interpolation as the model is forced to pass through all four points. If the points represent observa-
tions with a measurement error, then the resulting model coefficients are meaningless. In addition to the uncertainty of the model coefficient estimates, it should be kept in mind that the model is only designed to be used for prediction within the range of independent variables represented by the observation vectors.

The automatic controller's model optimization feature, described in section 2.1, is designed to determine the model coefficients that will produce a minimum mean square error prediction. The model (2.2.2.8) is compounded in the sense that the independent variable temperature predicts only the drying coefficient G as an intermediate step. This drying coefficient is required of a second model (2.2.2.5) which predicts the observed moisture content. Experience indicates that the same limitations apply to this optimized compound model as apply to the simpler regression solution. Using the optimized coefficients to predict the G coefficient for untested temperatures produced non-sensical predictions for G. For example, using the DT-1 coefficients in table A.3.1 to predict G for 80 degrees Fahrenheit produces a drying coefficient (G) larger than the .293 indicated for $110^\circ$F. This result is contrary to experience that suggests in the range of temperatures used to dry lumber, higher temperatures cause faster drying rates. Therefore the range of validity of this G coefficient from DT-1 is limited to $110^\circ$F to $180^\circ$F.
Table A.3.1

Calculated values for optimal model drying coefficients from tests DT-1 through DT-4
DRYING COEFFICIENT G

\[ G = (\beta_0 + \beta_1 \theta + \beta_2 \theta^2 + \beta_3 \theta^3)^2 \]

\( \theta = \text{Schedule Temperature} / 180 \)

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>G (DT-1)</th>
<th>G(^1) (DT-2)</th>
<th>G (DT-3)</th>
<th>G (DT-4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>*</td>
<td>.021</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>90</td>
<td>*</td>
<td>.127</td>
<td>*</td>
<td>*</td>
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<td>100</td>
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<td>.312</td>
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<td>110</td>
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<td>150</td>
<td>1.02</td>
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<td>1.09</td>
<td>1.10</td>
</tr>
<tr>
<td>160</td>
<td>1.63</td>
<td>2.47</td>
<td>1.40</td>
<td>1.38</td>
</tr>
<tr>
<td>170</td>
<td>2.61</td>
<td>2.94</td>
<td>*</td>
<td>1.75</td>
</tr>
<tr>
<td>180</td>
<td>4.12</td>
<td>3.43</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

\( \beta_0 = -1.6031 \quad 2.0539 \quad -1.2702 \quad -1.8758 \)

\( \beta_1 = 1.7100 \quad -6.0985 \quad .73225 \quad 3.7101 \)

\( \beta_2 = 3.4737 \quad 2.9119 \quad 1.8673 \quad -2.8835 \)

\( \beta_3 = -5.6067 \quad -.71241 \quad -2.9065 \quad -.4505 \)

* Presentation of G at this temperature would imply extrapolation of available test results

1 second phase of DT-2 only (after kiln shutdown)
Consider again a research investigation in which the first experiment is often only exploratory. The result of this first experiment is used to determine how many observations are needed to attain the specified model coefficient accuracy from the second experiment. In this way information about the model gained in one experiment is used to improve the design of the second experiment. Also, in some cases, observation vectors from both experiments might be combined to improve the estimate of the model coefficient even further after the second experiment is completed.

Similarly, information in the form of estimates of the drying coefficient can be combined to form a composite model providing even greater model improvement. For example, the G values in table A.3.1 could be used as observations of the dependent variable for a regression where schedule temperature is the independent variable. The initial drying coefficient model for an additional drying test (DT-5) could be the result of a polynomial regression that uses the entries in table A.3.1 for observation vectors. This composite table could then be expanded during DT-5 as soon as at least 5 successive moisture measurements are made. The model could be optimized to the measurements and the resulting model coefficients used to add a fifth column to table A.3.1. This fifth column would contribute additional observations to the composite regression model. As the set of observation
vectors for G expands due to measurement and model optimization of data from successive drying runs, the estimates of the regression coefficients which determine the composite drying coefficient G will be known with greater confidence. Thus the initial prediction is improved and the controller accuracy is enhanced. The procedure for using this adaptive feature is semiautomatic because the operator must perform the regression separately and use judgement in choosing the observations to be entered into the regression but there is no reason that the entire procedure can not be automated.

Summary

Model optimization is accomplished at two levels. At the primary level, the process is automatic. The operator submits the drying schedule and moisture measurement information to the computer controller. The computer responds with a set of coefficients which when incorporated into the moisture prediction model will produce a prediction that best fits the measurement data. For the range of temperatures represented by the schedule, this model is optimal (section 2.1)

In order to have the model predict well for temperatures outside this range, the model optimization is performed at the secondary level. In the present version of the controller this process is not automatic. The operator uses drying coefficient models optimized to
previous drying runs with the same species to generate a table of observation vectors (associated G coefficients and temperatures) similar to those in table A.3.1. This table can then be used as input to a regression. This procedure can be automated and the controller made truly adaptive once the best weighting factors for the observation vectors are decided upon.

The importance of this model optimization feature to kiln drying control cannot be over emphasized. This feature made it possible to improve an initially poor prediction of moisture content in DT-4 during a schedule update procedure. Without the model optimization feature, an automatic optimal controller would not be practical at this time because no model exists that produces a good drying prediction over the entire moisture content range when only the initial moisture content and species is known.
Appendix 4: Solution of the Incremental Hysteresis Model for Plastic Deformation

The objective of the elastic-plastic hysteresis model is to estimate the incremental plastic deformation at each point in time due to the loading history. This appendix presents the method outlined by Manson (1968) which is used in the kiln controller stress model to calculate the plastic deformation. First an overview of the procedure used is given, then every step is explained in detail. This procedure is subroutine 'STRESS' in the computer program listed in Appendix 6.

A.4.1 Overview of the Solution Procedure

The first element of the calculation is an estimate of the stresses based on equilibrium, assuming that all the changes in deformation will be elastic in nature. A test is then made to determine if this in fact does occur. If all the changes in strain calculated with the elastic model satisfy the equilibrium, geometric compatibility and force-deformation relations, then the calculation is finished. If not, an estimate of the lower limit of plastic deformation is made. This estimate and the equilibrium equation are used to calculate an upper limit for plastic deformation. The upper and lower estimates
are averaged. This average estimate and the equilibrium relation are used to generate another estimate. This procedure using the average for an estimate is repeated until the maximum uncertainty in the estimate is reasonably small. The limits for this maximum uncertainty are set so that the maximum total error for a 50 day simulation is 10%.

A.4.2 Equilibrium

Equilibrium is based on the premise that total strain ($\varepsilon_{BN}$) at all levels is constant and equal to the sum of unrestrained shrinkage strain ($\varepsilon_{SRC}$), plastic strain ($\varepsilon_{EPM}$) creep or viscous strain ($\varepsilon_{VEM}$) and elastic strain ($\varepsilon_i$). To satisfy equilibrium, the sum of the elastic stresses is zero or

$$\sum E_i \varepsilon_i = 0$$

$$\sigma_i = E_i \varepsilon_i$$

$$= E_i \left( \varepsilon_{BN} - \varepsilon_{SRC} - \varepsilon_{VEM} - \varepsilon_{EPM} \right)$$

(A.4.1)

$\sigma$ = stress

$E_i$ = modulus of elasticity

$i$ = level index which runs from 1 to 8

$C_i$ = constants derived from (2.2.3.1)
Solving for the total strain and accounting for all levels you get

\[ \varepsilon_{BN} = \frac{\sum \left( \varepsilon_{SRC_i} + \varepsilon_{VEM_i} + \varepsilon_{EPM_i} + \Delta \varepsilon_{EPM_i} \right) \cdot E_{1_i} \cdot C_i}{\sum E_{1_i} \cdot C_i} \]

(A.4.2)

\[ \varepsilon_{BN} = \text{average strain at the boundary} \]

\[ \Delta \varepsilon_{EPM_i} = \text{increment in plastic memory} \]

The stress weighting factor (C_i) depends on the spacing through the thickness of the lumped elements.

Once this total strain (\( \varepsilon_{BN} \)) is calculated, the total strain value for the spring element (\( \varepsilon_{TOT} \)) is

\[ \varepsilon_{TOT} = \varepsilon_{BN} - \varepsilon_{SRC} - \varepsilon_{VEM} \]

(A.4.3)

Then the elastic stress is

\[ \sigma_{1_i} = \left( \varepsilon_{TOT_i} - \varepsilon_{EPM_i} - \Delta \varepsilon_{EPM_i} \right) \cdot E_{1_i} \]

(A.4.4)
For the example shown in figure A.4.1, the value of $\varepsilon_{EPM}$ is zero. Since this is the first step in the calculation, $\Delta \varepsilon_{EPM}$ is also assumed to be zero. The value of $\Delta \varepsilon_{EPM}$ shown in the figure is the lower limit estimate of the plastic memory ($\Delta \varepsilon_{MLL}$ explained later) that results from this calculation. The associated stress calculated using the non-linear version of the stress-strain relationship and the total strain calculated above is

$$\sigma_2 = \sigma_e + (\varepsilon_{TOT} - \varepsilon_e)E_2$$

(A.4.5)

The values of $\varepsilon_{TOT}$, $\sigma_1$ and $\sigma_2$ are key inputs to the equations used to calculate the low limit estimate and upper limit estimate of plastic memory strain.

A.4.3 Transformation

If the stress changes sign as it does for example in figure A.4.2 a transformation is performed as shown. This transformation simplifies the computational procedure. The base coordinate for the stress-strain coordinate transformation is zero until the trajectory first crosses the zero stress axis and is equal to the associated plastic memory at the point of crossing. The procedure is to calculate $\sigma_1$, $\sigma_2$ and update the base coordinate for all thickness levels. If for any level, the condition
Figure A.4.1

Relationship of incremental plastic memory ($\Delta \varepsilon_{EPM}$) to stresses ($\sigma_1$, $\sigma_2$) and strain ($\varepsilon_{TOT}$) resulting from the equilibrium calculation.
Figure A.4.2
Absolute value coordinate transformation used to simplify the plastic memory calculation
Actual

Stress $\sigma$

Strain $\varepsilon$

$\varepsilon_{EPM}$

Transformed

$|\sigma|$

$|\varepsilon|$
If all levels are in the elastic region, the calculation is complete for this time step. If not, the plastic memory strain must be updated.

A.4.4 Low Limit Estimate of Plastic Memory Increment

The calculation of the low limit estimate for the increment in plastic memory ($\Delta \varepsilon_{\text{MLL}}$) is based on elastic stiffness. Since this is a stiffer system than the actual system, the resulting deformations are smaller.

$$\Delta \varepsilon_{\text{MLL}} = \varepsilon' - \varepsilon''$$

where $\varepsilon'$ and $\varepsilon''$ are the values in figure A.4.3 for an example with previous plastic deformation. The needed values of $\sigma_1$, $\sigma_2$ and $\sigma_{\text{TOT}}$ were provided by the equilibrium calculation.

$$\varepsilon'' = \sigma_2 / E_1$$

$$\varepsilon' = \varepsilon_{\text{TOT}} - \varepsilon_{\text{EPM}}$$

$$\varepsilon_{\text{EPM}} = \text{cumulative plastic memory prior to this iteration}$$

(A.4.6)
Figure A.4.3

Relationship of the low limit estimate of incremental plastic memory ($\Delta \varepsilon_{\text{MLL}}$) to existing plastic memory ($\varepsilon_{\text{EPM}}$), equilibrium stresses ($\sigma_1, \sigma_2$) and strain ($\varepsilon_{\text{TOT}}$)
A.4.5 Upper Limit Estimate of Plastic Memory Increment

The upper limit estimate is based on the premise that if an equilibrium calculation were done with the upper limit estimate for plastic memory ($\varepsilon_{MUL}$) shown in figure A.4.4 then the stress calculated using this upper limit memory estimate could be no greater than the elastic limit stress. To get this upper limit estimate $\Delta\varepsilon_{MLL}$ was added to $\varepsilon_{EPM}$ before calculating equilibrium. This yields a lower value of $\sigma_1$ from a repeated equilibrium calculation (see figure A.4.4)

\[
\Delta\varepsilon_{MUL} = \varepsilon' - \varepsilon''
\]

\[
\varepsilon'' = \sigma_1 / E_1
\]

\[
\varepsilon' = \frac{\sigma_1 - \sigma_{EL}}{E_2} + \varepsilon_{EL} - \varepsilon_{EPM}
\]

(A.4.7)

Now take the average of these two extreme estimates and add this average estimate to the existing plastic memory. Then perform the equilibrium calculation. Compare $|\sigma_1|$ with $|\sigma_2|$. If $|\sigma_1| > |\sigma_2|$

(A.4.8)

then the average estimate of memory is an under estimate.
Figure A.4.4

Relationship of upper limit estimate of incremental plastic memory ($\Delta \varepsilon_{\text{MUL}}$) to existing plastic memory ($\varepsilon_{\text{EPM}}$), the low limit estimate of incremental plastic memory ($\Delta \varepsilon_{\text{MLL}}$) and stress ($\sigma_1$)
Use this value to update the low limit estimate. Conversely, use this value to update the upper limit estimate if

$$|\sigma_1| < |\sigma_2|$$

(A.4.9)

A.4.6 Error Control

The maximum error in the estimate at any step in the iteration is

$$\text{max error} = \left| \frac{\Delta \varepsilon_{\text{MUL}} - \Delta \varepsilon_{\text{MLL}}}{2} \right| = \text{error } (n)$$

with each iteration, the error is halved or

$$\text{error } (n) \cdot \frac{1}{2} = \text{error } (n + 1)$$

$$\text{error } (n) \cdot (1/2)^m = \text{error } (n + m) = \frac{\text{error } (n)}{2^m}$$

$$2^m = \frac{\text{error } (n)}{\text{error } (n + m)}$$

$$m \ln 2 = \ln \left( \frac{\text{error } (n)}{\text{error } (n + m)} \right)$$
\[
\frac{\ln (\text{error (n)})}{\ln (\text{error (n + m)})} = \frac{m}{\ln 2}
\]

(A.4.10)

\(\ln = \text{natural logarithm}\)

\(m = \text{number of iterations required}\)

\(\text{error (n + m)} = \text{maximum error allowable for any step}\)

If the maximum error allowed for the entire simulation is 10% in say 500 steps and you expect .01 minimum total plastic strain then

\[
\text{maximum error/step} = \frac{\text{error (n+m)} \leq (10\%) \times 0.01}{500 \text{ steps}} = 2 \times 10^{-6}/\text{step}
\]

(A.4.11)

Now adding \(C_1\) to prevent computer overflow and 1 to compensate for truncation, the computer implemented formula is

\[
\text{NITER} = \text{INT} \left( \frac{\ln (\text{CONFAC})}{\ln 2} \right) + 1
\]

\[
\text{CONFAC} = \frac{\Delta \epsilon_{\text{MUL}} - \Delta \epsilon_{\text{MLL}}}{2} \cdot \frac{1}{2 \times 10^{-6}} + C_1
\]

(A.4.12)
CONFAC = convergence factor

INT = the truncation function

This form of error control eliminates any time consuming test for convergence. NITER is the limit set on a DO LOOP index.
Appendix 5: A Future Lumber Drying Controller

Based on the results of DT-4 reported on in section 3.2 the estimated computational cost of drying a charge of lumber with the controller in its present form is approximately $4000 (approximately $3 \times 10^9$ kilo-core seconds on the UNH DEC-10 system). This cost could eventually be reduced as the procedures are simplified. If after these changes in procedure the controller is still too expensive to operate for industrial use then a more efficient control algorithm will have to be used. Design of a more efficient algorithm requires attention to simplifying the model and using a more efficient search algorithm.

A.5.1 Simplified Model

Since most of the computational cost involved in an optimization search is spent in calculation of the performance index (cost of drying), a reduction in the number of discrete levels of the model would produce almost a proportional reduction in the amount of calculation required. The moisture is presently predicted at 5 levels throughout the board thickness. Five equally spaced locations were chosen so that the prediction could be compared directly with data from McMillen's study. The factors important to the drying cost calculation could
be estimated adequately with a three level drying model. The three levels would be at: 1. the lumber plant boundary, 2. a depth of one tenth the plant thickness so that the steep gradient near the surface may be adequately represented and 3. board center.

The cost factors can be adequately represented if the mechanical prediction is accomplished by a 3 level discrete model. The location of the levels would be the same as those used for the moisture prediction model. If the results of the followup test (DT-5) support the hypothesis that only the elastic-plastic element is necessary for effective control then the viscous memory element of the stress-strain element can be excluded. Exclusion of the viscous memory prediction will result in a large computational saving because the mechanical model is simplified from a dynamic model described by differential equations to an equality constraint on the moisture prediction. This simplification of the mechanical model to an algebraic model expressed by a piecewise linear relationship (Appendix A.4 and the equilibrium condition (2.2.3.1)) reduces the number of dynamic equations which must be integrated in order to generate the prediction.

The mechanical model might be simplified further by substituting the bistate elastic model scheme for hysteresis as suggested by Sinyak (1975) for the iterative scheme in Appendix A.4.
A.5.2 Optimization Algorithm

A more efficient search requiring fewer function evaluations could be designed by making use of conditions on the optimum derived using the calculus of variations. Kirk (1971) gives an excellent presentation of numerical techniques available using this variational approach. The most appropriate of these techniques for the wood drying problem is the gradient approach. The gradient approach will be more efficient than the simplex technique used in the present version of the controller since the gradient vector calculated at each step guides the search in the downhill direction.

Summary

Since a company often has many kilns operating simultaneously, and microprocessor technology is advancing at such a rapid pace, the design of the kiln control of the future should be based on the distributed computing concept. A microcomputer located at the kiln could automatically scan sensors for temperature, humidity, board moisture content and perhaps strain. The measured information would then be checked for consistency by the microprocessor.

If the air conditions required by the schedule and the wood conditions predicted by the model disagree significantly from predicted values then a schedule update as outlined in section 3.2 and Appendix A.6 would be required.
This is an operation which would be performed at a central time shared computer. In this manner, a central minicomputer could perform supervisory control of several kilns each drying different species.

The first step is to fully evaluate the present system with an additional drying test (DT-5). If the present controller performs satisfactorily then it would be of value to proceed with development of a more efficient controller using the gradient technique. Parallel development of the satelite microprocessor controller can begin immediately because with the exception of models for checking the consistency of the data all the required information is now available.

The development of a microprocessor controller should be treated as a separate problem. Such a device can be used to implement a suboptimal strategy such as a smoothed version of the present industrial standard drying schedules. The drying could be accelerated sooner in the drying cycle as no large transient stresses would be generated as a result of step changes. Rice (1978) is presently conducting research to implement a smoothed schedule with an electro-mechanical controller. The microprocessor could operate under more adverse conditions of heat, humidity, dust and vibration than the electro-mechanical controller. The microprocessor could also be programmed to detect sensor failure such as a wet sock drying out or a failure in the humidification system both of which
happen and have disastrous consequences for lumber quality. Upon detection of these failures, the microprocessor controller could be programmed to set off an alarm and safely shut down the kiln until repairs are made. For these reasons the microprocessor controller would be more reliable and flexible than any electromechanical controller.
Appendix 6: Computer Control Program

The computer control program listed in section A.6.2.2 can be used to control the drying of any species of hardwood lumber. The program already includes the mechanical constants for red oak. For other species, these constants would have to be changed. Since the objectives of drying soft wood lumber are so much different than drying hardwoods, considerable alteration would be required before the program could be used to dry softwoods.

The program is written in Fortran and designed to run on any general purpose computer system. Four elements; 1. the computer, 2. the program described here, 3. a general purpose statistical program capable of elementary statistics and multiple regression and 4. a human operator are all that is needed to form the feedback block of the drying system depicted in figure A.6.1. The actuator may be any conventional set point controller and the kiln any drying chamber with forced circulation and controlled temperature and humidity. The only requirement for control is the periodic estimate of the average moisture content of the load.

A.6.1 Control Procedures

All of the control procedures require preparation
Figure A.6.1

Drying System Block Diagram
of an input file, running the program and obtaining the results in an output file. Depending on the procedure, these results may then be either printed or plotted. The input file is composed of integer values used to specify which optional features of the program are to be used and set variable integer values in the prediction model. Also included in the input file are any real model coefficient variables necessary to completely specify the model. The variable integer quantities are stored in the Integer Work Vector (IW) (see section 2.1). The function of each element of this work vector is explained in the documentation section of the program listed at the end of this appendix. The floating point variables are likewise stored in the Real Work Vector (RW) discussed with the IW vector.

A.6.1.1 Schedule Optimization

Since it consumes a large amount of computer time, the schedule optimization procedure is designed to be run in the batch mode of operation. The operator first determines the drying model coefficients using the approach discussed in Appendix A.3. Then he enters this and other IW and RW settings he selects into the input file which must be named 'WDOPT.DAT'. This data file is stored on a magnetic disk which is read when the program is executed. The program will write the schedules and the associated drying costs representing each vertex of the simplex.
(see section 2.4) onto file WDOPT.DAT, the output file after each search iteration. The search will then halt when possible convergence is indicated, the limit of the number of iterations has been reached, or the allotted computer time has been exceeded.

It is important to keep in mind that this initial optimization procedure is only designed to determine the schedule for green lumber. If significant pre-drying has occurred then the schedule update procedure (section A.6.1.6) should be used first.

The result of the search is checked by the schedule sensitivity analysis procedure (section A.6.1.2). If necessary, a search with a narrower range of initial guesses near the best initial broad search may be conducted until the minimum drying cost schedule is determined.

An example of an initial version of file WDOPT.DAT is presented in figure A.6.2. The first line is identification information (up to 50 characters). The second line consists of only one integer (here = 10) which indicates the number of IW values to be specified. The next line, beginning with 4, includes the indices of the IW vector to be specified by the integer values in the following line in the same sequence as the indices (here = 10 each). In this example, IW(4) = 0, IW(5) = 50, etc. The following line is again a single integer (here = 15) which specifies the number of RW values to be read. With the free format reading procedure used, the next 15 values which specify
Figure A.6.2

Example of Initial Version of File WDOPT.DAT
DEMO VERSION OF WDOPT.DAT (VER 52 CF PRGRM)
10
4,5,5,12,13,15,21,24,27,40
0,50,1,0,1,0,5,7,2,175000
15
1,2,3,4,5,6
14,27,60
40,50,51,52,53,54
*11E-05,*11E-02,*16E-02,*375E-05,*755,1
*001,*1000,*
*788,*1,*875823,*710094,*-2.863458,*-4504703
RW indices may be grouped on any number of lines. In this example, the 15 RW indices are listed on the following three lines each beginning with the numbers 1, 14 and 40 respectively. The RW values corresponding to these indices are on the last three lines in the same order as the indices. All lines must be accounted for. Unused lines must have at least a zero entry. This WDOPT.DAT file determines what the program will do.

when the program is executed, the computer will read the file and perform the procedure option specified. Schedule optimization is the default procedure, therefore, no specific IW value is needed in the WDOPT.DAT file to determine an optional procedure. Depending on the computer, a record of computer messages will be kept and made available to the operator. Messages referring to underflow occur occasionally and can be ignored. A halt message may mean one of three things: 1. the search has converged to an optimum within the tolerance specified by RW(14), 2. the maximum number of iterations specified by IW(5) (here = 50) has been reached or 3. the computer time limit specified in milliseconds by IW(40) has been exceeded (here = 175000). This maximum computer time feature is designed to allow the program to be run in short segments giving it a higher priority in a time sharing situation and thus allowing it to run more often. Instructions are included in the batch control file to cause the program to be automatically resubmitted upon completion of a
segment of the search. Upon being reexecuted, the program reads the intermediate results from the updated version of the WDOPT.DAT file and picks up the search from where it left off. In this way the search runs in short segments at high priority until the search converges or the maximum number of iterations is reached.

Progress of the search can be monitored by reading the line printer file. An example of this file is presented in figure A.6.3. The first nine lines of the line printer file is an echo print of the IW and RW values specified by the WDOPT.DAT file. The column of numbers immediately following, here 11 entries long, is a listing of the performance index associated with each of the randomly selected schedules used to initialize the search. Following this is a sequence of 9 lines beginning with "X(1)= " and ending with "WRFILE STOP" representing the output for a search iteration. The first line labeled 'X(1)= ' lists the transformed EMC values. To get the actual EMC values, use equation (2.4.2). Likewise, the second line represents transformed temperature values. The third line lists the iteration number and the best performance value for all the schedules. A complete list of performance values follows (here, the next 11 values). The computer time is then listed. The next two lines, 'WRFILE START' and 'WRFILE STOP' signal the beginning and end of the WDOPT.DAT file update. The sequence then repeats for the next iteration.
Figure A.6.3

Example of a Line Printer File
Since file WDOPT.DAT is updated after each iteration, progress of the search may be more closely followed by examining this disk file. An example of the file used in figure A.6.2 at the 50th iteration is depicted in figure A.6.4. The information originally contained in the input file (figure A.6.2) is preserved and listed in the resultant updated file (figure A.6.4). In addition, the schedules and their associated drying costs are also listed. For example, the first schedule listed begins on the 10th line of the file. The first line across lists the EMC values (in round numbers 18.7, 15.9, 14.3, 6.8, 7.8). The next line is a list of the temperature values. The following line is a single number which is the drying cost associated with this schedule (here = .5551418). Below this schedule are listed the 10 other schedules that define the simplex. Progress of the search is gauged by the difference in drying costs. The costs for all the schedules should be equal to three significant figures before the simplex can be considered converged.

To determine if a converged simplex specifies a true minimum cost, the schedule sensitivity analysis procedure is performed. This procedure is explained in the next section (A.6.1.2). If the result of the sensitivity analysis suggests that the original search must be carried beyond 200 iterations then a search with initial random guesses over only a subset of the entire space is recommended. An example of the initial WDOPT.DAT file for
Figure A.6.4
Update Version of File WDOPT.DAT
such a reduced search is illustrated in figure A.6.5. This example picks up where the original search result (figure A.6.4) left off but requires that additional RW values be specified. The vector elements RW(101) through RW(105) specify the EMC values and RW(141) through RW(145) specify the temperature values for the best schedule from figure A.6.4. The perturbation values RW(15) and RW(16) specify the range of the random perturbation of EMC and temperature needed to randomly generate the initial guess schedules for the new search. As documented in figure A.6.6, the lowest drying cost has been improved from .5551418 in figure A.6.4 to .5131091 in figure A.6.6. The EMC values and temperature values for these examples were specified at 0, 20, 40, 60, and 80 days. This time spacing may not be the best and future research should be directed toward spacing the values more closely, especially during critical periods of the drying schedule.

The values of IW and RW used in these examples were chosen for illustration only. The minimum set of values for a schedule optimization is listed in table A.6.1. The indices of the IW and RW vectors listed represent those variables that cannot be assumed to be default values.

A.6.1.2 Schedule Sensitivity Analysis

The sensitivity analysis procedure is designed to check whether a schedule resulting from a search is locally
Figure A.6.5

Initial WDOPT.DAT File for a Reduced Search
DEMO SEARCH SUBSPACE (VER 52 CF PRGRM)
10
4,5,6,12,13,15,21,24,27,40
0,50,1,0,1,0,5,7,2,17500
27
1,2,3,4,5,6
14,27,60
15,16
101,102,103,104,105
141,142,143,144,145
40,50,51,52,53,54
-1E-05,-1E-02,-1E-02,-375E-05,-756,1
001,1,-1000
10,-40,
18,-2,15,-2,16,3,5,8,7,9
109,111,94,147,115
-783,1,-1,875,823,3,710064,-2.883458,-.4504703
Updated WDOPT.DAT File for a Reduced Search
Table A.6.1

Minimum set of non-default IW and RW parameters for next computer drying test schedule optimization
INTEGER WORK VECTOR

IW(4) = 0 current iteration
IW(5) = 200 maximum iteration
IW(12) = 0 simplex read control
IW(13) = 1 new random start
IW(31) = 0 schedule update option
IW(32) = 0 schedule sensitivity analysis option (if = 1, the program performs a schedule sensitivity analysis)

REAL WORK VECTOR

RW(1) through RW(6) drying cost weighting factors
RW(1) = .0000154 heat factor
RW(2) = .000956 time factor
RW(3) = .0144 MC factor
RW(4) = .0000205 stress factor
RW(5) = .985 strain
RW(6) = 1.0 failure
RW(14) = .0001 simplex convergence factor
RW(21) = desired target moisture content
RW(40) = 1.0 drying model coefficient
RW(50) = .1
RW(51) through RW(54)
RW(55) = 45 shrinkage threshold
RW(56) = 750 shrinkage divisor (= 45/.06)
RW(60) = 1667 bias stress for failure prediction
optimum. The input file for this procedure is a modified version of the WDOPT.DAT file resulting from the optimum schedule search. The only modification required is setting IW(32) equal to 1. Upon execution, the program instructs the computer to read the best schedule (lowest vertex) existing in the WDOPT.DAT file. Each EMC and temperature in this schedule is varied one at a time to determine the effect on the drying cost. If the best schedule is optimum then all of these modified schedules should produce a higher drying cost. The EMC values are varied by an amount equal to RW(15) and the temperature perturbation is RW(16). These perturbation values should be set to the value of control accuracy of the kiln (EMC \( \pm 1\% \), temperature \( \pm 2^\circ F \)). The output results of this procedure are written into file SNA.DAT.

At the beginning of the SNA.DAT output file illustrated in figure A.6.7, the header information from the WDOPT.DAT file is repeated, then the sensitivity analysis of the best schedule follows. The cost indices are the coefficients for the economic model (see section 2.3). Then each schedule is listed beginning with the one being analyzed followed by each additional version with either the EMC or the temperature changed. On the line immediately below each schedule are listed the six components of the drying cost followed by the total drying cost and the normalized performance difference. The normalized performance difference is defined by
Figure A.6.7

Example of a SNA.DAT File
<table>
<thead>
<tr>
<th>Schedule</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.195E-1</td>
<td>9.656E-01</td>
<td>9.144E-01</td>
<td>7.269E-01</td>
<td>0.6766E-02</td>
<td>0.342E+00</td>
<td>0.305E+00</td>
<td>0.596E+01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.195E-1</td>
<td>0.665E-01</td>
<td>9.144E-01</td>
<td>0.6766E-02</td>
<td>0.342E+00</td>
<td>0.305E+00</td>
<td>0.596E+01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.195E-1</td>
<td>0.665E-01</td>
<td>9.144E-01</td>
<td>0.6766E-02</td>
<td>0.342E+00</td>
<td>0.305E+00</td>
<td>0.596E+01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.195E-1</td>
<td>0.665E-01</td>
<td>9.144E-01</td>
<td>0.6766E-02</td>
<td>0.342E+00</td>
<td>0.305E+00</td>
<td>0.596E+01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.195E-1</td>
<td>0.665E-01</td>
<td>9.144E-01</td>
<td>0.6766E-02</td>
<td>0.342E+00</td>
<td>0.305E+00</td>
<td>0.596E+01</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- SCHEDULE: 
- 2: 5.195E-1, 9.656E-01, 9.144E-01, 7.269E-01, 6.6766E-02, 0.342E+00, 0.305E+00, 0.596E+01
- 3: 5.195E-1, 0.665E-01, 9.144E-01, 0.6766E-02, 0.342E+00, 0.305E+00, 0.596E+01
- 4: 5.195E-1, 0.665E-01, 9.144E-01, 0.6766E-02, 0.342E+00, 0.305E+00, 0.596E+01
- 5: 5.195E-1, 0.665E-01, 9.144E-01, 0.6766E-02, 0.342E+00, 0.305E+00, 0.596E+01
- 6: 5.195E-1, 0.665E-01, 9.144E-01, 0.6766E-02, 0.342E+00, 0.305E+00, 0.596E+01
- 7: 5.195E-1, 0.665E-01, 9.144E-01, 0.6766E-02, 0.342E+00, 0.305E+00, 0.596E+01
- 8: 5.195E-1, 0.665E-01, 9.144E-01, 0.6766E-02, 0.342E+00, 0.305E+00, 0.596E+01
- 9: 5.195E-1, 0.665E-01, 9.144E-01, 0.6766E-02, 0.342E+00, 0.305E+00, 0.596E+01
- 10: 5.195E-1, 0.665E-01, 9.144E-01, 0.6766E-02, 0.342E+00, 0.305E+00, 0.596E+01

- Schedule values are in scientific notation.
\[ \text{NPD} = \frac{(P(I) - \text{OBJP})}{\text{OBJP}} \]  
\[ \text{(A.6.1)} \]

NPD = Normalized Performance Difference  
OBJP = Performance or drying cost of the object schedule (the best schedule from search)  
P(I) = Performance of the Ith schedule

With the exception of the first schedule listed where the NPD = 0, all the values of NPD should be positive for an optimum object schedule. In some cases, where one result is negative but very small, the object schedule may still be considered acceptable.

A.6.1.3 Simulation

Aside from the expected applications for interactive simulation, the simulation procedure for operating the computer program is designed to produce a detailed schedule or an estimate of the starting state for purposes of an updated schedule optimization. The input for this procedure includes the file W01TRJ.DAT in addition to the WDOPT.DAT file. The W01TRJ.DAT file contains values of IW, RW and the schedule values (stored in vector U) which may be read on command (type AF or AFE) while in the simulation mode. An example of a W01TRJ.DAT file is illustrated in figure A.6.8. The format is one vector element
Figure A.6.8

Example of a WOLTRJ.DAT File
per line (index first then value). Values for the IW vector are at the top of the file followed by RW values (with the 0,0 entry separating the two) followed by schedule values. The simulation procedure is entered by executing the program with IW(15) = 1 in the WDOPT.DAT file (no other procedures specified).

Once the program begins execution, the IW and RW values in WDOPT.DAT will be printed at the terminal followed by 'AR,TR,AT,TI,AU,TU,AF,AFE,AX1,ES,RUN,PLT,FIN?'. This last line prompts the operator with the command options available. If the operator then types AR (accept an RW value), the computer will then request the index and value for the RW (work vector) value the operator wishes to specify or alter. This information is entered (numbers only) in free format in the same order as requested by the computer. The TR command will cause RW values to be typed at the terminal. The range of indices will be requested and must be typed in the order of low index first (free format, numbers only) then upper index. The AI,TI,AU,TU apply to IW vector and U vector (schedule), values respectively. The AF (accept file) command is used to read in the W01TRJ.DAT file. The AFE command is equivalent to AF with the addition of an echoprint at the terminal. The AX1 (accept vector XI) puts the best schedule from the information read in from the WDOPT.DAT file into the U vector for simulation purposes. The ES (echo schedule) command will type out the schedule to be simulated. The
RUN command will begin the simulation. Before beginning the simulation make sure the target moisture content value (RW(21)) and maximum simulation time (RW(26)) are equal to the desired values. The computer time in milliseconds, the simulation time and the number of iterations required for convergence of the elastic-plastic model calculation are typed at the terminal. A large number of iterations required by the elastic-plastic model indicates a large jump in either stress or strain. If this occurs and the schedule is properly defined then a smaller time step should be used if the additional computer time is allowed. The PLT (graphics mode) command caused the program to branch to the graphics mode subroutine. This should be used to display the results of the simulation. The FIN (finish) command exits the program.

When the results of the schedule search are simulated and stored in the output file WDOUTP.DAT, the result is the schedule. The optional information saved is determined by the specified output option IW(21) (see the documentation section of the program listing for options). An optional output, file RSTRT.DAT (restart file), is used during the schedule update procedure and will be discussed in section A.6.1.6. For situations such as DT-4 where the actual schedule values fluctuated so irregularly from the desired values, the filtered schedule simulation should be used. The simulation schedule is specified by a fifth order time polynomial. The polynomial coefficients are
determined by regression and specified to the schedule instead of EMC and temperature (see IW(16) in the documentation section of the program listing). The fluctuation in EMC and temperature is simulated by control noise (see IW(33), IW(34), IW(35)) as illustrated in figure 3.2.10 and 3.2.11.

A.6.1.4 Graphics

All graphs in this thesis were produced using a computer program in the graphics mode, a tektronix graphics terminal and a program developed at UNH to convert the information into a form suitable for plotting on a CALCOMP plotter. Although this special capability is available at UNH, any installation has a printer plotted graphic output. The input for the plot is stored in two files. The model prediction (simulation results) is stored in file WDOUTP.DAT. The first three variables in WDOUTP.DAT (columns in the file) are time, temperature and EMC. The remaining variables depend on the simulation output option selected. The data input for plotting is stored in file INPLT.DAT. The first row of the INPLT.DAT file contains the number of rows and the number of columns of data in the remainder of the file (one column per variable) in free format. The output of this procedure is the file PIC.DAT which contains the plot to be printed.

The graphics mode is entered from the simulation mode by typing the PLT command when prompted. The compu-
ter will then request if prediction or data information is to be read. Upon completing the input task, the computer will prompt the user with 'PRED, DATA, VARLST, LBLY, LBLX, LBLTTL, SCALE, PRPLT, TGPLT, CALCMP, FIN?'. The PRED (predicted variables) command is used to pick the column numbers of the variables from the WDOUTP.DAT file that are to be included in the plot. The Index (column number) of the independent variable will be requested first. The answer to this question is usually '1' for time. Since multiple plots are allowed, the quantity and column numbers of the dependent variables are then requested. The DATA command accomplishes the same operation for the information stored in file INPLT.DAT. The VARLST (variable list) types the indices of the variables to be plotted. The plot labeling commands (LBLY (Y axis), LBLX (X axis), LBLTTL (title)) must be followed by an alpha numeric character string (50 characters or less) once the user is prompted by a carriage return. The SCALE command is used to set the limiting values for the graph axes. The user will be prompted to type the limits. The PRPLT (print plot) command will cause the graph to be stored in file PIC.DAT. A 'yes' response to the prompt 'TYPE OUT GRAPH?' will cause a reduced version of the PIC.DAT file to be typed at the terminal so that the graph may be checked before being plotted. The TGPLT (Tektronix Graphics plot) and CALCMP (Calcomp plot) commands are designed to be used with particular supporting
software available only at UNH. Therefore at other facilities, dummy subroutines are used so that only the PRPLOT command will result in a graph. The FIN command will return the program to the simulation mode.

A.6.1.5 Model Optimization

The model optimization procedure discussed in sections 2.2.2 and A.3 is similar to a schedule optimization. The principle difference is that the EMC and temperature values are replaced in the latter by drying model coefficients and the drying cost is replaced by the mean square error for the moisture model prediction. Figure A.6.9 is an example of an input WDOPT.DAT file. To produce a model optimization, a step approximation to the schedule must first be specified. For the example in figure A.6.9, the actual schedule is approximated by three (RW(100)) EMC values: RW(101), RW(102) and RW(103) and three (RW(140)) temperature values specified at 0, 9.5 and 13.5 days. In addition, a DTCM.DAT file as shown in figure A.6.10 is required as input. The first line contains only the number of rows that follow. All seven columns must be filled. Zeros are used if data is not available. The first column contains the time in days, the second through the sixth contain average moisture content at slice levels one through five respectively and the last column contains the estimate of the average moisture content of all the wood in the charge. The primary output
Figure A.6.9

Example of a WDOPT.DAT File for Model Optimization
SSA1NS26 MODDFT DT4(T-1.5)
15
1,2,3,4,5,6,12,13,15,16,21,24,26,28,40
1,4,5,9,200,1,0,1,0,2,5,7,4,2,175000
19
14,15,16,26,27
100,101,102,103
121,122,123
140,141,142,143
161,162,163
0,001,0,2,19,1,0
3,15,16,16
0,9,5,13,5
3,124,115,105
0,9,5,13,5
Figure A.6.10

Example of a DTCM.DAT File for Model Optimization
for this procedure is the updated WDOPT.DAT file illustrated for this example in figure A.6.11. The RW information is followed by the last five lines in the file. The first four items on each line are the model coefficients. The last item is the Mean Square Error of the prediction. In addition to this output, a detailed listing of the prediction errors for the best model can be obtained by setting IW(10) = 1 and IW(15) = 1 in the WDOPT.DAT file. Then when prompted by the simulation command string type 'RUN'. When prompted again type 'FIN' and print the DTCMPT.DAT file for the output (see figure A.6.12). The recommended minimum set of parameters for the model optimization procedure is listed in table A.6.2.

A.6.1.6 Schedule Update

The schedule update procedure is designed to compensate for inability to track the desired schedule and for inadequacies of the prediction model. The first step of this procedure is to perform a model optimization using measured moisture content data. As discussed in Appendix A.3, the model information is combined with data from previous tests to determine an updated drying model. To generate an estimate of the lumber state, this model is then used along with the simulation of the measured and projected drying conditions until the anticipated time of switchover to the new schedule. The lumber state is saved on file RSTRT.DAT as shown in figure A.6.13. The first
Figure A.6.11

Example of an updated WDOPT.DAT File for the model optimization procedure
Figure A.6.12

Example of a DTCMFT.DAT File
| i  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 |
| 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 | 0.10000000 |

The table contains numerical data, possibly related to some scientific or technical measurements. The values are listed in a sequence that suggests a grid or matrix format, typical of data tables used in experiments or calculations.
Table A.6.2

Minimum set of non-default IW and RW parameters for model optimization
MINIMUM SET OF NON-DEFAULT IW AND RW PARAMETERS
FOR MODEL OPTIMIZATION

IW(2) = 4  number of model coefficients
IW(3) = 5
IW(4) = 0
IW(5) = 200
IW(12) = 0
IW(13) = 1
IW(26) = depends on drying data available (see program listing)
IW(28) = 2
IW(40) = 175000
RW(14) = .0001
RW(15) = 0  offset for initial guess coefficients
RW(16) = 2  range for initial guess coefficients
RW(100) = number of EMC steps in the schedule
RW(101) through RW(100 + RW(100)) EMC values
RW(121) through RW(120 + RW(100)) times of EMC steps
RW(140) number of temperature steps
RW(141) through RW(140 + RW(140)) temperature steps
RW(161) through RW(160 + RW(140)) times of temperature steps
Figure A.6.13

Example of an RSTRT.DAT File
| 0.1529401E+01 | 0.3209519E+02 | 0.1192330E+05 | 0.3520062E+02 |
| 0.1620000E+02 | 0.1750000E+02 | 0.2261956E+02 | 0.2743719E+02 |
| 0.3529150E+02 | 0.3689000E+02 | 0.4229656E+02 | 0.4318311E+02 |
| 0.1533513E+01 | 0.2511696E+02 | 0.2000000E+02 | 0.2000000E+02 |
| 0.1000000E+03 | 0.3000000E+00 | 0.3000000E+00 | 0.3000000E+00 |
| 0.817375E-02  | 0.1000000E+01 | 0.7789999E-02  | 0.1234566E-02 |
| 0.195111E-02  | 0.195111E-02  | 0.195111E-02  | 0.195111E-02  |
| 0.195230E-04   | 0.6516733E-04 | 0.6516733E-04 | 0.6516733E-04 |
| 0.1000000E+00 | 0.1000000E+00 | 0.1000000E+00 | 0.1000000E+00 |
| 0.2392475E+02 | 0.1000000E+01 | 0.1000000E+01 | 0.1000000E+01 |
| 0.123784E+02  | 0.123784E+02  | 0.123784E+02  | 0.123784E+02  |
| 0.8796535E+02 | 0.123784E+02  | 0.9999999E+02 | 0.9999999E+02 |
| 0.1230933E+02 | 0.2309333E+02 | 0.2309333E+02 | 0.2309333E+02 |
| 0.1799221E-01 | 0.7792986E-02 | 0.892993E-02  | 0.354441E-04  |
| -0.639755E-03  | -0.397554E-03 | -0.997554E-03 | -0.997554E-03 |
A schedule optimization will use this as the starting state if IW(31) = 2. As with the initial schedule, the answer from this update optimization should be checked by using the sensitivity analysis procedure. When a satisfactory solution is reached then a simulation should be run to generate a new schedule in the WDOUTP.DAT file. The graphics procedure can be used if the operator prefers a graphical output.

A.6.2 Computer Program Description

All the computer subroutines are organized around a main program (see figure A.6.14) which initializes all integer switches (vector IW) and all real variable parameters (vector RW). The program then reads file WDOPT.DAT for non-default settings of these two vectors. From this point, the program then does a sensitivity analysis (subroutine SNA), goes into a simulation mode (subroutine
ONETRJ), or generates the initial simplex (subroutine INISIM) for an optimization search. The simplex vertices for the optimization search are array X. In the main loop, these vertices and their associated vectors are sorted in ascending order (subroutine SIMRNK). An output update to both the line printer and WDOPT.DAT is accomplished. Then a check is made to determine if allotted Central Processor Time (CPU) has been exceeded.

Next, a step is made in the search (subroutine SIMPLX) and followed by a check convergence. If converged, the centroid of the simplex should be the lowest point. If not, return to the beginning of the loop.

A.6.2.1 Subroutine Descriptions

**Subroutine INISET** (Initial settings for vectors IW and RW)

This subroutine sets the default values for the integer work vector IW and the real work vector RW.

**Subroutine SIMPLX** (Simplex optimization search)

Subroutine SIMPLX performs a function minimization search. It requires an array of \((n-1)\) vertices where \(n\) is the dimension of the search space. There are three operations involved in the search process. The first operation is reflection of the high point of the simplex through the centroid of the n
Figure A.6.14

Computer Program Block Diagram
lower points. The second is expansion or a further projection along the line defined by the highpoint and the centroid of the n lower points. The third is a contraction or a shorter projection. This algorithm is explained in detail in an article by Nelder and Mead (1965).

**Subroutine SIMRNK** (Rank the simplex)

This subroutine sorts the column vectors based on their associated function values (row n-1). The technique used is a "bubble" sort.

**Subroutine ONETRJ** (One Trajectory Simulation)

Entry into this subroutine puts the program into the simulation mode.

**Subroutine SNA** (Sensitivity Analysis)

This subroutine is designed to test the best vertex of an answer from an optimization run. This is accomplished by perturbing each of the EMC values by an amount equal to RW(15) and perturbing each of the temperature values by an amount RW(16). The result is the 'Normalized Performance Difference' (NPD) defined by formula (A.6.1).
Subroutine **INISIM** (Initial Simplex)

This subroutine generates a starting simplex and evaluates all the vertices. This may be a pseudo-random list for the temperature sequence of the schedule being optimized or the model coefficients if a model optimization is being performed. An option available with this subroutine is a pseudo-random start identical to one used before and stored in the file WDOPT.INI. This feature is designed for studying the effect changes in the program may have on the efficiency of the optimization search.

Subroutine **RDFILE** (Read from File)
Read available information from file 'WDOPT.DAT'.

Subroutine **WRFILE** (Write to File)
Write to file 'WDOPT.DAT' assigned values of IW, RW and X that define the state of the search algorithm.

Subroutine **RDWRTE** (Read-Write)
This subroutine contains the order and indices of variables in file 'WDOPT.DAT'.

Subroutine TRANS (Transform)
Using trigonometric functions, this subroutine transforms coordinates from the unconstrained space required by the simplex search algorithm into coordinates that represent temperature and EMC. The temperature and EMC values are constrained to exist within practical upper and lower limits.

Subroutine TRNINV (Inverse Transform)
This subroutine accomplishes the inverse of the transform in subroutine TRANS.

Subroutine FUNCT (Function)
This subroutine calculates the performance index or function value associated with the input vector $U$. In the situation where $U$ corresponds to a temperature schedule then the function value is the cost to dry the lumber. If $U$ is a trial set of drying model coefficients, as would be the case for the model optimization option, then the function value would be the mean square error. Take the square root of this value to get RMS error.
**Subroutine CMMOD** (Concentration of Moisture (prediction) Model)

This subroutine predicts the concentration of moisture at the next time step as determined by the time interval (RW(37)), the time interval between steps. The prediction is based on difference equations where G, the analog of the diffusion coefficient, is a function of temperature or temperature and moisture.

**Subroutine STRESS** (Stress-Strain Model)

This subroutine calculates stress and strain components in the drying board. Using the input moisture concentrations, the shrinkage sources are first calculated. Again using the moisture concentrations as well as the input temperature, the physical constants for the force deformation model are estimated. Equilibrium for an elastic model is also calculated. If any of the stresses indicate that the elastic limit has been exceeded then a low limit estimate of the plastic memory is calculated. Using this low limit estimate, equilibrium is again calculated. Using all this infor-
mation, an upper limit estimate of the plastic memory increment is made. Based on the difference of these two estimates, low limit and upper limit, the number of iterations required for the desired convergence accuracy is calculated. For the calculated number of iterations, successively finer estimates of the memory increment are made.

Once this new stress state is established, the increment of tensile work is calculated and added to the work integral. The integral is compared with the estimate of work limit. In addition the creep strain is incremented. If the appropriate switches are set then the strain output is calculated. This output includes elastic strain and set as measured by the slicing technique. Also included is an estimate of how much the slice bends when it is cut free, as well as, how much bending should occur during the standard prong test. If the time is appropriate or if the stress state has taken an unusually large jump, the model state is written into the WDOUTP.DAT file. At the end of the simulation a
more complete set of information is written into this data file.

**Subroutine EQLBM** (Equilibrium Calculation)
Using an estimate of plastic memory increment, this subroutine calculates the total stress and strain.

**Subroutine VISCOM** (Viscous Flow Model)
This subroutine calculates an estimate of creep. The force-deformation relationship is determined by a Maxwell model. The creep strain is not incremented if it causes the total strain to exceed preset limits. This viscous memory limit is estimated to be a factor of elastic strain. The creep component of tensile work is also updated.

**Subroutine OUTP** (Output)
This subroutine outputs information to the file WDOUTP.DAT.

**Function SIGEL** (Sigma Elastic Limit Stress)
This subroutine calculates the elastic limit stress as determined by short term tests conducted by Youngs (1957).

**Function SIGMAX** (Maximum Tensile Stress)
This subroutine calculates maximum stress in tension as determined from short term stress tests by Youngs (1957).

**Function EPSMAX** (Maximum Strain in Tension)

This subroutine calculates maximum strain in tension as determined by Youngs (1957).

**Function STIFF** (Stiffness of the Material Modulus of Elasticity)

This subroutine calculates the modulus of elasticity for wood. This estimate is based on regression equations presented by Youngs (1957).

**Function Y**

This function sets $Y$ equal to the algebraic expression of the form used by Youngs to describe elastic limit stress, maximum stress, maximum strain and stiffness.

**Subroutine INPUT** (Humidity and Temperature Control Inputs to the Drying Lumber)

This subroutine generates simulated temperature and humidity in the kiln.

**Subroutine COST** (Cost of Drying)
This subroutine calculates the cost of drying the lumber. The cost is the sum of six components, 1) energy, 2) time to target moisture and 3a,b,c and d are components of final product quality. The first quality cost 3a is related to the final moisture concentration gradient. Even though the average concentration of moisture may be at the desired level the shell and core may not be. The second component of final quality, 3b, is residual stress. The actual stress values are calculated in subroutine STRESS and are multiplied by an economic conversion coefficient in this subroutine. The same is true of the last two final quality factors, 3c and 3d, which are plastic deformation and failures.

**Subroutine ISTATE** (Initial State)
This subroutine either saves the system state on file RSTRT.DAT or reads the file information into array STTINI. This array is then used to generate the initial state in subroutine FUNCT.

**Subroutine SIMCAL** (Simplex Calculation)
This subroutine calculates the function
value associated with every vertex of the simplex.

**Subroutine TRAJ1** (Trajectory 1)
This subroutine calculates the function only for the vertex in column 1.

**Subroutine CNTOUT** (Centroid Output)
This subroutine evaluates the function value for the centroid of the simplex. If at final iteration this function value is the lowest value then put this vertex into column 1 of the matrix X.

**Subroutine STOPIT** (Stop it)
When called, this subroutine generates a halt, stopping the program.

**Subroutine ITIME** (Integer Time)
This subroutine determines the computer running time since last called for as an integer value representing milliseconds.

**Subroutine OPTPLT** (Optimization Plotting)
This subroutine sets up the arrays required by subroutines PRPLT, TGPLT and CALCMP for graphics generation.

**Subroutine PRPLT** (Print Plot)
This subroutine creates the Print Plot
in file PIC.DAT.

**Subroutine CALCMP** (Calcomp Computer)

This subroutine generates information to be plotted directly.

**Subroutine TGPLT** (Tektronix Graphics)

This subroutine generates a plot on the Tektronix Graphics terminal.
A.6.2.2 A Fortran Listing of the Program
2=TEKTRONIX GRAPHICS TERMINAL
1=PICTURE ON DISK ONLY
2=PICTURE ON TERMINAL ONLY
3=PICTURE ON DISK AND TERMINAL (SEE FOR20.DAT)
THIS PARAMETER IS SET AFTER THE TGLT COMMAND
IS GIVEN
26=DRYING MODEL OPTIMIZATION OPTION
1=LEVEL
2=LEVEL
3=LEVEL SHELL-CORE
4=AVG FOR THE POPULATION
5=AVG, SHELL, AND CORE
DATA FILE IS ALWAYS THE SAME FORMAT
TIME, LEVEL1-LEVEL5, AVERAGE (SEVEN ITEMS)
IF NO DATA FILE IN WITH ZEROS
I(W(26))=4
27=FAILURE CRITERION OPTION
1=STRESS
2=GCD
3=TRAIN
I(W(27))=2
28=OPTIMIZATION OPTION
1=SCHEDULE
2=MODEL (CMOD)
I(W(28))=1
29=DEBUG CEBUG OUTPUT (I=YES)
I(W(29))=0
30=DEBUG FOR MAIN PROGRAM
I(W(30))=0
31=RESTART SWITCH (I=1, SAVE SYSTEM STATE
IF=2, INITIALIZE FUNC FROM ARRAY STTN
IF=3, DE LET 1 AND 2
CAUTION: INSURE FILE RSTRT.DAT IS AVAILABLE
I(W(31))=0
32=SENSITIVITY ANALYSIS SWITCH
(IF=1, DO SENSITIVITY ANAL AND STOP)
I(W(32))=0
33=AND LIMITED CONTROL INPUT NOISE FOR SIMULATION
34=OPTION NUMBER
0=GEN NOISE
1=SQUARE #VE
2=RANDOM UNIFORM DISTRIBUTION
3=GAUSSIAN DISTRIBUTION
I(W(33))=0
35=INTERVAL CHANGE COUNTER SETTING
1=CHANGE EVERY TIME STEP
2=CHANGE EVERY OTHER TIME STEP
3=CHANGE EVERY J+1 TIME STEP
I(W(34))=0
36=PHASE CONTROL FOR SQUARE WAVE
1=OUT OF PHASE
2=IN PHASE
I(W(36))=0
CALL TIME(X,Y)
CALL SETRAN(X,Y)
40=TIME[IN WATSE] TO RECORD SIMPLEX AND STOP (BEFORE CPU TIME LIMIT)
I(W(40))=266600
I(W(41))=266600
41=HANDLE INDICES FOR OUTPUT OPTION 7 (THEI I(W(41))=266600
45=STOP SWITCH[IF=1, TPJ CALC IS STOPPED]
50=100 IS FEADER INFO

***REAL WORK VECTOR R
1-10 COST FACTORS 1=HEAT LCSS, 2=TIME, 3=CM(T), 4=RES STRESS,
5=SET, 6=PERCENT FAILURES
(FILE=DOPT.DAT)

9=ZERO, A FILLER FOR DOOUTP.DAT
  R=9=0.
10=
11=20 SIMPLEX ADMIN
12=
13=PERFORMANCE INDEX=COST
14=DESIRED CONVERGENCE FACTOR(FILE=DOPT.DAT)
15=PERTURBATION EXC.(OR OFFSET FOR MCMD OPT)
16=PERTURBATION TEMPERATURE(RANGE OF INITIAL GUESSES FOR MCMD OPT)

SEE BELOW FOR DEFAULT PERTURBATION VALUES
17=MINIMUM KILN E4C
   R=(17)=0.
18=MAXIMUM KILN E% C
   R=(18)=20.
19=MINIMUM KILN TEMPERATURE
   R=(19)=105.
20=MAXIMUM KILN TEMPERATURE
   R=(19)=180.
21=55 MODEL ADMIN
22=TARGET MOISTURE CONTENT
   R=(22)=0.
23=
24=TARGET TEMPERATURE
25=TIME
26=MAX TIME ANY TRAJECTORY
   R=(26)=80.
27=E4C MULTIPLIER
   R=(27)=1.0
30=RELATIVE TEMPERATURE ABOVE AMBIENT WHEN SLICING OCCURS
   R=(30)=1.0
31-36 COST VALUES
37=DELTA SIM TIME
   R=(37)=1.
NCISE AMPLITUDE
38=E4C ISO AMPLITUDE OR STD DEVIATION
   R=(38)=0.
39=TEMP AMPLITUDE OR STD DEVIATION
   R=(39)=0.
40-99 STATE OF THE PHYSICAL SYSTEM
40=0 MULTIPLIER (CM#CC OPT 6,7)
   R=(40)=1.
41=HELPFUL CONTENT, SURFACE TC CENTER
   R=(41)=0.
42=AVG FOR THE D4RC
43=MODEL COEFFICIENTS(40,50=54)
   R=(43)=0.
44=DOYING COEFFICIENTS
   R=(44)=1.
<table>
<thead>
<tr>
<th>Line</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>51-54</td>
<td>COEFF USED TO DETERMINE G</td>
<td>00023200</td>
</tr>
<tr>
<td></td>
<td>RW(51)=0.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RW(52)=G.</td>
<td>00023220</td>
</tr>
<tr>
<td></td>
<td>RW(53)=G.</td>
<td>00023400</td>
</tr>
<tr>
<td></td>
<td>RW(54)=0.</td>
<td>00023500</td>
</tr>
<tr>
<td>55-58</td>
<td>SHRINKAGE STRAIN COEFFICIENTS (55-58)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RW(55)=30.</td>
<td>00023700</td>
</tr>
<tr>
<td></td>
<td>RW(56)=SHRINK CIVISCR (FOR SHRINK CM)</td>
<td>00023900</td>
</tr>
<tr>
<td></td>
<td>RW(57)=SHRINK PERTURBATION CM=0.</td>
<td>00024000</td>
</tr>
<tr>
<td></td>
<td>RW(58)=SHRINK PERTURBATION CM=80.</td>
<td>00024100</td>
</tr>
<tr>
<td>59-60</td>
<td>BIAS STRESS FOR FAILURE PREDICTION (59-60)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RW(59)=40.</td>
<td>00024200</td>
</tr>
<tr>
<td></td>
<td>RW(60)=60.</td>
<td>00024300</td>
</tr>
<tr>
<td>61-66</td>
<td>SIGMA (STRESS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>69=1 FACTOR</td>
<td>00024400</td>
</tr>
<tr>
<td></td>
<td>70=2 FACTOR</td>
<td>00024500</td>
</tr>
<tr>
<td></td>
<td>RW(70)=6666666667</td>
<td></td>
</tr>
<tr>
<td>71-78</td>
<td>EPSLT (TOTAL ELASTIC-PLASTIC STRAIN COMPONENT)</td>
<td>00025600</td>
</tr>
<tr>
<td></td>
<td>79=EPSSE (RELEASE STRAIN)</td>
<td>00025700</td>
</tr>
<tr>
<td></td>
<td>80=EPSSE85</td>
<td>00025800</td>
</tr>
<tr>
<td>81-88</td>
<td>EPSPM (TOTAL VISCOUS STRAIN)</td>
<td>00025900</td>
</tr>
<tr>
<td></td>
<td>99=CREEP RATE FACTOR</td>
<td>00026000</td>
</tr>
<tr>
<td></td>
<td>RW(99)=1.</td>
<td>00026100</td>
</tr>
<tr>
<td>89-94</td>
<td>EPSVEE (TOTAL VISCOUS STRAIN)</td>
<td>00026200</td>
</tr>
<tr>
<td></td>
<td>95=CREEP FACTOR TENSILE</td>
<td>00026300</td>
</tr>
<tr>
<td></td>
<td>96=CREEP FACTOR COMPRESSION</td>
<td>00026400</td>
</tr>
<tr>
<td></td>
<td>RW(95)=1.</td>
<td>00026500</td>
</tr>
<tr>
<td></td>
<td>RW(96)=1.</td>
<td>00026600</td>
</tr>
<tr>
<td></td>
<td>RW(97)=1.</td>
<td>00026700</td>
</tr>
<tr>
<td>ENCM</td>
<td>101-120</td>
<td>00026800</td>
</tr>
<tr>
<td>TIMES</td>
<td>121-140</td>
<td>00026900</td>
</tr>
<tr>
<td>TESTP</td>
<td>141-160</td>
<td>00027000</td>
</tr>
<tr>
<td>TIMES</td>
<td>161-180</td>
<td>00027100</td>
</tr>
<tr>
<td></td>
<td>RW(161)=END OF WARMING THROUGH PERIOD</td>
<td>00027200</td>
</tr>
<tr>
<td></td>
<td>THE FOLLOWING IS A COMPLETELY RANDOM START</td>
<td>00027300</td>
</tr>
<tr>
<td></td>
<td>UNIFORM DISTRIBUTION IN PHYSICAL SPACE</td>
<td>00027400</td>
</tr>
<tr>
<td></td>
<td>FC, A SCHEDULE</td>
<td>00027500</td>
</tr>
<tr>
<td></td>
<td>SET THE ENCM AND TEMPERATURE</td>
<td>00027600</td>
</tr>
<tr>
<td></td>
<td>RW(120)=0.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>RW(121)=0.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DC 1 1=1.5</td>
<td>00027700</td>
</tr>
<tr>
<td></td>
<td>RW(100+1)=10.</td>
<td>00027800</td>
</tr>
<tr>
<td></td>
<td>RW(140+1)=130.</td>
<td>00027900</td>
</tr>
<tr>
<td>SET THE TIMES</td>
<td>RW(121+1)=2*(23)/(1*(11)-1)+RW(120+1)</td>
<td>00028000</td>
</tr>
<tr>
<td></td>
<td>RW(161+1)=2*(26)/(1*(11)-1)+RW(160+1)</td>
<td>00028100</td>
</tr>
<tr>
<td>I CONTINUE</td>
<td>PERTRHAFIC ABOUT STARTER ENCM</td>
<td>00028200</td>
</tr>
<tr>
<td></td>
<td>RW(15)=20.</td>
<td>00028300</td>
</tr>
<tr>
<td></td>
<td>PERTRHAFICATION ABOUT STARTER TEMPERATURE</td>
<td>00028400</td>
</tr>
<tr>
<td></td>
<td>RW(16)=100.</td>
<td>00028500</td>
</tr>
<tr>
<td></td>
<td>181-188=MAXIMUM STRAIN</td>
<td>00028600</td>
</tr>
</tbody>
</table>
******** END OF OUTPUT CONTROL ****************************

UPDATE ITERATION CLUSTER

[Code]

CALL SIMPLEX(X,RW,IN)
14 CONTINUE

TEMPORARY JUMP CENTRIC CHECK AT END
IF(RM(13).LE.RM(14)) GO TO 998
ELSE
GC TO 1

******** END OF MAIN LCCP ****************************

FINISHED ?

9 CONTINUE

ANSWER IS CENTROID OF FINAL SIMPLEX
IF CENTROID IS HIGHER THAN LOWEST VERTEX
DC ANOTHER 10 ITERATIONS AND TEST AGAIN
CALL CTCUT(X,RW,IN)
IF(IM(6).EQ.0) GC TO 18
IF(IM(4).GT.MAXIT) GO TO 19
CENTROID IS TCC HIGH
WRITE(IM(8),119)
119 FORMAT(' CENTROID IS TCC HIGH, CONTINUE')
GO TO 1
18 WRITE(IM(6),114)
114 FORMAT(' FINISHED')
CALL *FILE(X,RW,IN)
GO TO 999
998 CONTINUE
CALL STCPIT
999 STOP

END

SUBROUTINE SIMPLEX(X,RW,IN)
IMPLICIT DOUBLE PRECISION(A-Z,0-2)
DIMENSION X(34.34),X(50),XSTAR(50),XSTAR(50),XSTAR(50),RW(300),
N(100)
OPTIMIZATION STRATEGY(ALPHA=1,DELTA=1/2, GAMMA=2)

CALCULATE CENTROID OF LCER 1n(2) POINTS

DO 55 J=1,IN(2)
A=XBAR(I,J)*3.0
55 CONTINUE

DO 56 J=1,IN(2)
A=XBAR(I,J)*3.0
56 CONTINUE

CALCULATE REFLECTION
IF(IM(29).EQ.1) WRITE(IM(9),107)

107 FORMAT(' W(9),107')
X2STR(1) = 3*XSTAR(1) - 2*XBAR(1)
65 CONTINUE
EXPANSION
IF(IW(29) .EQ. 1) WRITE(IW(8),108)
108 FORMAT(10X,'EXPANSION')
   1X(10) = 0
   CALL FUNCTION(X2STR,RW,1X)
   Y2STR = RX(12)
   IF(IW(29) .EQ. 1) WRITE(IW(8),114) Y2STR
114 FORMAT(10X,'Y2STR(2)',E16.7)
   IF(Y2STR .LT. X(IW(3),1)) GC TC 3
ELSE
   IF(IW(29) .EQ. 1) WRITE(IW(8),109)
109 FORMAT(10X,'FAILED EXPANSION')
   4 DC 66 = [1,1X(2)
   X(IW(3),1) = XSTAR(1)
   66 CONTINUE
   X(IW(3),1) = Y2STR
   TEST FCR MINIMUM
   GO TO 7
   3 DD 67 = [1,1X(2)
   X(IW(3),1) = X2STR(1)
   67 CONTINUE
   X(IW(3),1) = Y2STR
   CHECK IF *MINIMUM HAS BEEN REACHED
   7 YAVG = 0.
   DD 68 = [1,1X(3)
   YAVG = YAVG + (X(IW(3),1) / (1W(3)))
   68 CONTINUE
   SUMSC = 0.
   DD 69 = [1,1X(3)
   SUMSC = SUMSC + (X(IW(3),1) - YAVG) * (X(IW(3),1) - YAVG) / (1W(3))
   RETURN
END

******************************************************************************

ADMINISTRATIVE SUBROUTINES

******************************************************************************

SUBROUTINE CNETRF(X*,F*,W)
DIMENSION X(34,34),U(50),UT(50)
DATA [FILE,TERM,1,5]*
DATA KHELL* / *
502 FORMAT(1X,'*F(*)=*',I3)
504 FORMAT(1X,'*F(*)=*',E16.7)
506 FORMAT(1X,'*U(*)=*',E16.7)
100 CONTINUE
WRITE(TERM,101) KHELL
101 FORMAT(1X,'*A1=*',A10,T,A1,TL,AF,A,*A1,*ES,FUN,PLT,F1N*)
READ(TERM,102) X.MS
102 FORMAT(A3)
IF(NANS.EQ.'Ar') GC TO 1
IF(NANS.EQ.'Tr') GC TO 2
IF(NANS.EQ.'At') GC TO 3
IF(NANS.EQ.'Ti') GC TO 4
IF(NANS.EQ.'Au') GC TO 5
IF(NANS.EQ.'Tu') GC TO 6
IF(NANS.EQ.'Af') GC TO 7
IF(NANS.EQ.'AFe') GC TO 8
IF(NANS.EQ.'Es') GC TO 9
IF(NANS.EQ.'Pb') GC TO 901
IF(NANS.EQ.'Run') GC TO 902
IF(NANS.EQ.'A1') GC TO 903
IF(NANS.EQ.'F1n') GC TO 999
WRITE(TERM,100)
104 FORMAT(1X,'ANS NOT RECOGNIZED')
GO TO 100
7 CONTINUE
8 CONTINUE
OPENUNIT=1, FILE='C1TRJ.DAT')
10 CONTINUE
READ(FILE,* J,* (J)
IF(NANS.EQ.'AFe') WRITE(TERM,502) J,* (J)
IF(J.EQ.0) GO TO 11
GO TO 10
11 CONTINUE
READ(FILE,* J,* (J)
IF(NANS.EQ.'AFe') WRITE(TERM,504) J,* (J)
IF(J.EQ.0) GO TO 12
GO TO 11
12 CONTINUE
READ(FILE,** J,** (J)
IF(NANS.EQ.'AFe') WRITE(TERM,508) J,** (J)
IF(J.EQ.0) GC TO 13
GO TO 12
13 CONTINUE
CLOSEUNIT=1, FILE='C1TRJ.DAT')
GO TO 100
5 CONTINUE
WRITE(TERM,509) (U(1),I=1,1,* (11))
505 FORMAT(1X,'5** 5,SP7.1)
WRITE(TERM,** 19) (W(120+1),I=1,1,** (11))
516 FORMAT(1X,'** 19,SP7.1)
WRITE(TERM,** 11) (U(1),I=1,(11)+1,** (21))
510 FORMAT(1X,'** 11,SP7.1)
WRITE(TERM,** 20) (F(160+1),I=1,** (11))
520 FORMAT(1X,'** 20,SP7.1)
GO TO 100
1 CCNTINUE
3 CONTINUE
WRITE(TERM,101)
103 FORMAT(1X,'INP3 INDEX AND VALUE')
IF(NANS.EQ.'Ar') GC TO 15
READ(TERM,** J,** (J)
WRITE(TERM,504) J,** (J)
GO TO 100
15 CCNTINUE
IF(NANS.EQ.'A1') GC TO 10
READ(TERM,** J,** (J)
WRITE(TERM,502) J,** (J)
397
CALL SETRAH(Y)
DO 2 J=1,1M(3)
ADD RANCRYL TO STARTER IN PHYSICAL SPACE
DO EMC START
DO 3 K=1,1M(11)
YFL=RAN(QM)
U(K)=Rw(100*K)-Rw(15)/2+YFL*Rw(15)
HARD LIMITS
IF(U(K)>Gw(13)) L(K)=Rw(18)
IF(U(K)<Lw(17)) U(K)=Rw(17)
3 CONTINUE
DO TEMPERATURE START
DO 10 K=1,1M(1)+1,1M(2)
YFL=RAN(QM)
L(K)=Rw(13E+K)-Rw(10)/2+YFL*Rw(16)
IF(U(K)>Gw(20)) U(K)=Rw(20)
IF(U(K)<Lw(19)) U(K)=Rw(19)
10 CONTINUE
CALL TRAHV(U+UT+Rw,11)
DO 4 I=1,1M(2)
X(I,J)=UT(I)
4 CONTINUE
CALL FUNCT(U+Rw,11)
X(I(3),J)=Rw(12)
WRITE(1,501) X(I,J),I=1,1M(3))
WRITE(1,501) X(I(3),J))
501 FCR=0.7(SE16,7)
2 CONTINUE
CLOSE(UNIT=1,FILe='WDPT.INI')
Iw(12)=1
RETURN
6 CONTINUE
OPEN(UNIT=1,FILE='WDPT.INI')
DO 7 J=1,1M(3)
READ(1,501) X(I,J),I=1,1M(3))
7 CONTINUE
CLOSE(UNIT=1,FILe='WDPT.INI')
GO TO 988
200 CONTINUE
CALL TIME(X,Y)
CALL SSTREAM(Y)
Rw(15)=OFFSET
Rw(16)=PERFECTION
DO 202 J=1,1M(3)
DO 201 I=1,1M(2)
YFL=RAN(QM)
UT(1)=Rw(15)-Rw(16)/2+YFL*Rw(16)
201 CONTINUE
DO 202 I=1,1M(2)
X(I,J)=UT(I)
202 CONTINUE
CALL FUNCT(U+Rw,11)
X(I(3),J)=Rw(12)
WRITE(1,501) X(I(3),J))
203 CONTINUE
998 CONTINUE
Iw(12)=1
999 RETURN
END
SUBROUTINE TRANSF(XIN, XOUT, FR, *XI)

END

DO 2 CONTINUE
    XI = XI + 1
    IF (XI.EQ.0) GO TO 2
    2 CONTINUE

100 DIMENSIONS XIN(50), XOUT(50)
INT T(NC+4), X(NC+4)
CALL TRANSF(XIN, XOUT, FR)

END
IMPLICIT DOUBLE PRECISION(A-H,O-Z)
DIMENSION XIN(50),XOUT(50),Rw(300),iW(100)

INPUT (XIN) IS IN PHYSICAL SPACE
OUTPUT (XOUT) IS IN SIMPLEX SPACE
IF (iW(28)) .EQ. 2 GO TO 2
IF (iW(16)) .EQ. 4 GO TO 2
DO 1 I=1,iW(11)
XOUT(I)=ASIN((XIN(I)-(RW(17)+RW(18)))/(RW(13)-RW(17)))/2)
1
CONTINUE
GO TO 999
2 CONTINUE
DC 3 I=1,iW(2)
XOUT(I)=XIN(I)
3 CONTINUE
999 RETURN
END

SUBROUTINE CNTOUT(X,Rw,iW)
IMPLICIT DOUBLE PRECISION (A-H,O-Z)
DIMENSION X(34,34),Rw(300),iW(100),XCNTRD(34),
1 XIN(50),XOUT(50),U(50)
WRITE(iW(8),101)
101 FORMAT(' CNTOUT CH')
DO 1 I=1,iW(2)
XCNTRD(I)=C.
1 CONTINUE
DO 2 J=1,iW(3)
2 CONTINUE
DO 2 I=1,iW(2)
XCNTRD(I)=XCNTRD(I)+X(1,I)/iW(3)
2 CONTINUE
DC 5 I=1,iW(2)
51 XIN(I)=XCNTRD(I)
CALL TRANS(XIN,XOUT,Rw,iW)
WRITE(iW(6),102) XCLT(I),I=1,iW(2))
102 FORMAT(1'I.F10.1')
EVALUATE THE CENTROID
CALL FUNCT(XCNTRD,Rw,iW)
WRITE(iW(8),103) X(I(3),I),YCNTRD,I=1,iW(3)
103 FORMAT(' CVNT=H,CNTRD,LOW,SUVEQ,SLPSQMIN+W,
2 3E16.7)
IF NOT AT FINAL ITERATION, DON'T CHANGE SIMPLEX
IF (iW(4)) .LT. iW(5) GO TO 3
IF (iW(6))=0
1
IF (XCNTRD(I(3)) GT X(I(3),I)) I=I+1
IF (XCNTRD(I(3)) LT X(I(3),I)) GO TO 3
IF CENTER IS LOW=SET, REPLACE LOWEST VERTEX
WITH THE CENTROID
THIS IS AN ADDED TASK ON THE SIMPLEX
DO 4 I=1,iW(2)
X(I,1)=XCNTRD(1)
4 CONTINUE
X(I(3),1)=YCNTRD
3 WRITE(iW(9),102)
}
106 FORMAT(//1X,'TRAJECTORY')
11 CONTINUE
OPTIMIZE SCHEOLE OF CMMOD ?
   IF(1W(28).EQ.2) GC TO 200
   CALL TRANS(L,LT,P1,1)

SCHEDULE OPTIMIZATION

INITIALIZATION
   ADMINISTRATIVE

END OF TRAJECTORY FLAG
   IW(9)=0
UNLESS CONTINUE SWITCH IS ON
   IF(IW(17).EQ.1) GC TO 2
   IF(IW(31).EQ.2) GC TO 6
   IF(IW(21).EQ.3) GC TO 6
NEW START
COST DUE TO FAILURES
   R*(22)=G.
INITIAL ENERGY EXPENDED
   R*(31)=0.
TIME
   R*(25)=0.
INITIAL C* DISTRIBUTION
   CC 12 J=1.0
   R*(40+J)=R*(200+J)
12 CONTINUE
   CMMXSH=R*(44)+R*(45))/2.
   CMMNCF=R*(46)+R*(47))/2.
   R*(26)=(R*(41)+2.*R*(42)+3.*R*(43)+3.*R*(44)+CMMXSH)/10.
   CALL INPUT(UT,RW,IW)
MECHANICAL PARAMETERS
   00116500
   00116500
   00116500
   00116500
   00116500
   00116500
   00116500
   00116500
   00116500
   00116500
   00116500
DC 9 J=1.0
   EPSPM(J)=0.
   EPSYM(J)=0.
   EPFWR(J)=0.
   BASCO(J)=0.
   DPHO(J)=0.
   SIGMA(J)=0.
   EPSCTT(J)=0.
CUMULATIVE TENSILE WORK
   RW(210+J)=0.
9 CONTINUE
   GC TO 7
6 CONTINUE
FAIL
   R*=22)*STTIN(1,1)
TIME
   R*(25)*STTIN(1,2)
HEAT COST
   R*(31)*STTIN(1,3)
   R*(40)*STTIN(1,4)
ETNESS
   DC 8 J=1.8
   R*(40+J)*STTIN(2,J)
   EPSPM(J)=STTIN(3,J)
   EPSYM(J)=STTIN(4,J)
EPMER(J)=STTINI(E,J)
BASCO(J)=STTINI(0,J)
OMITS(J)=STTINI(7,J)
CUM WDFK
RM(210+J)=STTINI(E,J)
SIGMA(J)=STTINI(G,J)
EPSXTS(J)=STTINI(16,J)
8 CONTINUE
GO TO 2

7 CONTINUE
END TRAJ INITIALIZATION

MAIN LOOP
1 CONTINUE
CALL STRESS(RM,1)
CALL CSTUT(RM,1)
TEST FOR END OF TRAJECTORY
STOP IF C MALL TARGET
IF(RM(45),LE,RM(211)) GC TO 50
STOP IF TIME,GE,MAX TIME
IF(PA(25),GE,RM(26)) GC TO 50
STOP IF STOP SWITCH IS ON
IF(I(M);EQ,1),GC TO 50
2 CONTINUE
RM(25)=RM(25)+RM(37)
CALL INPUT(RM,1)
3 CONTINUE
CALL CMOD(RM,1)
GC TO 1
50 CONTINUE
IF(I(M);1),EQ,1) GC TO 16
IF(I(M);EQ,3) GC TO 16
ELSE
GO TO 17
16 CONTINUE
SAVE THE STATE OF THE PHYSICAL SYSTEM
CLOSE(UNIT=1,FILE= 'wDOUTP.DAT')
IF(I(M);1) CALL ISTATE(RM,1)
IF(I(M);NE,2) GC TO 900
I(M)=11
CALL ISTATE(RM,1)
I(M)=3
900 CONTINUE
OPEN(UNIT=1,FILE= 'wDOUTP.DAT',ACCESS='APPEND')
17 CONTINUE
IF(I(M);EQ,1) GC TO 998
TERMINAL COSTS
I(M)=1
CALL CSTUT(LR,M)
IF(I(M);EQ,1) WRITE(FILE,102) UT(I(M));
1 (RM(30+1),I,M,1,6)
IF(I(M);EQ,1) WRITE(INTERM,102) UT(I(M));
1 (RM(30+1),I,M,1,6)
102 FORMAT(1X,1,6)
DC IS [1,6]
EC FT(20+1)=RM(30+1)*RFT(1)
15 CONTINUE
IF(I(M);EQ,1) WRITE(FILE,102) UT(I(M));
1 (RM(30+1),I,M,1,6)
IF(I(M);EQ,1) WRITE(INTERM,102) UT(I(M));
00119200
00119300
00119400
00119500
00119600
00119700
00119800
00119900
00120000
00120100
00120200
00120300
00120400
00120500
00120600
00120700
00120800
00120900
00121000
00121100
00121200
00121300
00121400
00121500
00121600
00121700
00121800
00121900
00122000
00122100
00122200
00122300
00122400
00122500
00122600
00122700
00122800
00122900
00123000
00123100
00123200
00123300
00123400
00123500
00123600
00123700
00123800
00123900
00124000
00124100
00124200
00124300
00124400
00124500
00124600
00124700
00124800
00124900
00125000
00125100
INITIALIZE
RW(25)=0.
CALL INPUT(U,W,W)
DO 202 J=1,5
RW(40+J)=RW(200+J)
202 CONTINUE
CMXSF=(RW(44)+RW(45))/2.
CMXCF=(RW(46)+RW(47))/2.
RW(260)=(RW(41)+2*RW(42)+3*RW(43)+3*RW(44)+CMXSM)/10.
RW(261)=(CMXCF+5*RW(67)+4*RW(46))/10.
CALL INPUT(U,W,W)
203 CONTINUE
MAIN LOOP
DO 204 I=2,NDPTS+1
IFM=ABS(RW(25)-DATA(I))
IF( IFM<1PCT,DATA(I+1) ) GO TO 204
ELSE
FIT OPTIONS
1=6 LEVEL
2=5 LEVEL
3=2 LEVEL STELL=CGFE
#AVG
5=HELL,CCFE,AVAGE
IF( (Y+I,EQ.1) GC TC 221
IF( (Y+I,EQ.2) GO TO 222
else
IF( (Y+I,EQ.3) GC TC 223
IF( (Y+I,EQ.4) GC TC 224
IF( (Y+I,EQ.5) GC TC 225
#FIT ENTER (25E)
255 FORMAT(1X,LM#ECG#IZE CM#QD OPTION*)
CALL STOPIT
221 CONTINUE
CMERR(1)=DATA(1,10)-RW(41)
SUMGCSUMG=CMERR(1)**2/(6.*NDPTS)
DO 226 J=1,6
CMERR(J-2)=DATA(1,J+7)-RW(40+J)
SUMGCSUMG=CMERR(J-2)**2/(6.*NDPTS)
226 CONTINUE
IF( (Y+I,EQ.1) GC TC 204
ELSE
WRITE( IFILE,251 ) RW(25),DATA(I,1),RW(24),RW(23),
1 CMERR(J),J=1,6,(DATA(1,J,J),J=10,15),SUMG
251 FORMAT(1X,16F6.1,E16.7)
GO TO 204
222 CONTINUE
CMERR(1)=DATA(1,2)-(RW(41)+RW(44))/2.
SUMGCSUMG=CMERR(1)**2/(5.*NDPTS)
DO 227 J=1,5
CMERR(J)=DATA(1,J+1)-(RW(42)+J+RW(42+J))/2.
SUMGCSUMG=CMERR(J)**2/(5.*NDPTS)
227 CONTINUE
IF( (Y+I,EQ.1) GC TC 204
ELSE
WRITE( IFILE,253 ) RW(25),DATA(I,1),RW(24),RW(23),
1 CMERR(J),J=1,5,(DATA(1,J,J),J=2,6),SUMG
253 FORMAT(1X,16F6.1,E16.7)
GO TO 204
223 CONTINUE
CMERR(1)=DATA(1,2)-FA(260)
CMERR(2)=DATA(1,6)-FA(261)
00131200
00131200
00131400
00131600
00131600
00131700
00131800
00131900
00132000
00132100
00132200
00132200
00132200
00132300
00132400
00132500
00132600
00132700
00132800
00132900
00133000
00133100
00133200
00133300
00133400
00133500
00133500
00133500
00133600
00133700
00133800
00133900
00133900
00134000
00134100
00134200
00134300
00134400
00134500
00134600
00134700
00134800
00134900
00135000
00135100
00135200
00135300
00135400
00135500
00135600
00135700
00135800
00135900
00136000
00136100
00136200
00136300
00136400
00136500
00136600
00136700
00136800
00136900
00137000
00137100
DJ 228 J=1,2
SMSG=SMSG*(CMERR(J)*2)/(2.*NDPTS)
228 CONTINUE
IF(I*110.+NE+1) GC TO 204
ELSE
WRITE(FILE,258) RW(25),DATA(I,1),RW(24),RW(23),
CMERR(J),J=1,2,RW(260),Rw(261),SMSG
258 FORMAT(1X,8F6.1,E14.7)
GC TO 204
224 CONTINUE
CMERR(1)=DATA(I,7)-RW(49)
SMSG=SLMSG*(CMERR(1)*21)/NDPTS
IF(I*10.+NE+1) GC TO 204
ELSE
WRITE(FILE,258) RW(25),DATA(I,1),RW(24),RW(23),
CMERR(J),J=1,2,RW(260),Rw(261),SMSG
256 FORMAT(1X,8F6.1,E14.7)
GC TO 204
225 CONTINUE
CMERR(1)=DATA(I,2)-RW(260)
CMERR(2)=DATA(I,6)-RW(261)
DO 229 J=1,3
CMERR(J)=DATA(I,7)-RW(49)
229 CONTINUE
SMSG=SMSG*(CMERR(J)*2)/(3.*NDPTS)
229 CONTINUE
IF(I*10.+NE+1) GC TO 204
ELSE
WRITE(FILE,257) RW(25),DATA(I,1),RW(24),RW(23),
CMERR(J),J=1,2,RW(260),Rw(261),RW(49),SMSG
257 FORMAT(1X,10F6.1,E14.7)
GC TO 204
204 CONTINUE
IF(RW(25).GE.RW(261)) GC TO 997
ELSE
R(25)=RW(25)+*49(37)
CALL INPUT(U,F,R,1)
CALL CMMD(CW,1)
GO TO 2C3
997 IF(I*10.+SO+,1) CLCSE(UNIT=1,FILE=DTCHMFT,DAT*)
Rw(12)=SMSG
U(13)=SMSG
996 RETURN
END
SLECURTINE CMMD(FW,1W)
DIMENSION FW(300,1W(100),CM(8),G(9),CMGT(8)
DIMENSION ETA(6,6),CMTP(6),DTIBTA(3),CMG(5)
DIMENSION CAPAC(6),GFAC(8)
DATA CAPAC/-1.2,2.2,6.1,15.6,3.1,1.5/,
DATA GFAC/1.1,1.5,5,25,25,25,25/,
DATA DTIBTA/3,5,4,8,03/,
DATA IFIL,INTERP/-1./,
DATA CMGT/1.2,3.5,6.8,8.5,4.5/,
GC TO (51,52,53,54,55,56,57,58,59),IN(24)
WRITE(INTERP,501)
501 PCWAT(I*,ERROR CMWCC CPTION=*,15)
51 CONTINUE
53 CONTINUE
CONTINUE
GO TO 568
54 CONTINUE
55 CONTINUE
GENERATE G AS A RESULT OF CUBIC ON CM FOR SIMULATIONS AT CONSTANT TEMPERATURE
AS McMILLAN &D DONE
DO 17 J=1,8
CM(4)=CM(1)+CM(4)/2.
DO 18 J=2,5
CM(J)=CM(J+2)+CM(J+3)/2.
17 CONTINUE
CM(1)=CM(1)+CM(4)/2.
DO 18 J=2,5
CM(J)=CM(J+2)+CM(J+3)/2.
18 CONTINUE
DO 19 J=4,6
G(J)=R*(S1)*R(W(52))*CMG(J-3)/80*+
1 R*(S2)*CMG(J-3)*2/I400*+
2 R*(S3)*CMG(J-3)/512000/.
G(J)=G(J)*G(J)*R(W(40))
19 CONTINUE
GO TO 34
56 CONTINUE
GENERATE G AS A FUNCTION OF CM AND THETA
DO 21 J=1,8
CM(J)=W(R(40)+J)
21 CONTINUE
CM(1)=CM(1)+CM(4)/2.
DO 22 J=2,5
CM(J)=CM(J+2)+CM(J+3)/2.
22 CONTINUE
DO 33 J=4,6
G(J)=R*(S1)*R(W(52))*CMG(J-3)/80*+
1 R*(S3)*CMG(J-3)*2/I400*+
2 R*(S3)*CMG(J-3)/512000/.
G(J)=G(J)*G(J)*R(W(40))
33 CONTINUE
GO TO 34
57 CONTINUE
DC 35 J=1,8
CM(J)=F(W(R(40)+J)
35 CONTINUE
GENERATE G AS A FUNCTION OF THETA ONLY FOR TEMPERATURES BELOW 1100 F USE 1100 F G VALUE
THETA=R*(24)
TH=CM(G(W(S1))*R(H(52))*THETA/180*+
1 R*(S3)*THETA**2)/32400*+
1 R*(S3)*THETA**3)/5832000.+
DO 23 J=1,8
G(J)=TH*G*TH*W(R(40))
23 CONTINUE
GO TO 34
58 CONTINUE
TRUE 8 LEVEL DRYING MODEL
DO 680 J=1,8
CM(J)=F(W(R(40)+J)
680 CONTINUE
G HAS CUBIC DEPENDENCE ON TEMPERATURE
THETA=R*(24)
TH=CM(G(W(S1))*R(H(52))*THETA/180*+
1 R*(S3)*THETA**2)/32400*+
1 R*(S3)*THETA**3)/5832000.+
DO 681 J=1,8
G(J)=TH*G*TH*W(R(40))*GFA(J)
681 CONTINUE
584 CONTINUE
       RW(41)=RW(23)*(CMI(1)-RW(23))**EXP(-RW(37)/RW(50))
      00155200
      DO 582 J=2,7
      00155300
      RW(40+J)=RW(37)*G(J)*CMI(J-1)/CAPFAC(J)+
      00155400
      1   (1-G(J)+G(J+1))*RW(37)/CAPFAC(J))**CMI(J)+
      00155500
           2   RW(37)**G(J+1)*CMI(J+1)/CAPFAC(J)
      00155600
      582 CONTINUE
      00155700
      RW(48)=RW(37)**G(8)*CMI(7)/CAPFAC(8)+
      00155800
      1   (1-RW(37)**G(8)/CAPFAC(8))*CMI(8)
      00155900
      RW(49)=0.
      00156000
      DO 583 J=1,8
      00156100
      RW(49)=RW(49)+RW(40+J)*CMWGT(J)/40.
      00156200
      583 CONTINUE
      00156300
      GO TO 59
      00156400
      59 CONTINUE
      00156500
      GEN G AS A FACT OF CF* T-HETA FCF & LEVEL MODEL
      00156600
      DO 591 J=1,8
      00156700
      CMI(J)=RW(40+J)
      00156800
      591 CONTINUE
      00156900
      DO 592 J=2,8
      00157000
      CMG(J)=(CMI(J-1)+CMI(J))/2.
      00157100
      592 CONTINUE
      00157200
      DO 593 J=2,8
      00157300
      G(J)=G(1)+RW(52)**CMG(J)/80.*RW(53)**RW(24)/190.*
      00157400
      1   RW(54)**CMG(J)**RW(24)**14400.
      00157500
      G(J)=G(J)**G(J)+RW(40)
      00157600
      593 CONTINUE
      00157700
      GO TO 59
      00157800
      59 CONTINUE
      00157900
      RETURN
      00158000
      END
      00158100
      997 CONTINUE
      00158200
      CMXSM=(RW(44)+RW(45))/2.
      00158300
      CMXCM=(RW(46)+RW(47))/2.
      00158400
      RW(261)=(RW(41)+2.*RW(42)+3.*RW(43)+3.*RW(44)+CMXSM)/10.
      00158500
      RW(261)=(CMXCM+5.*RW(47)+4.*RW(48))/10.
      00158600
      999 RETURN
      00158700
      END
      00158800
      STRESS CALCULATIONS
      00158900
      SUBROUTINE STRESS(RW,SW)
      00159000
      DIMENSION RW(30),SW(110),AE CC(8),BETA(4),STFWGT(8),
      00159100
      1   SIGI(8),*
      2   SIGA2(E),EPSI(E)
      00159200
      DIMENSION CEPERM(E),CEPMLL(E),CEPMUL(E),EPSPRM(E),
      00159300
      1   EPSPRM(E),*
      00159400
      DIMENSION CEPFM(E),VWCSGA(E),CEPMAX(E)
      00159500
      DIMENSION CI(6),E2(E),SCFL(9),EPSFL(9),SGX(8),EPMX(E)
      00159600
      DIMENSION CM(8),EPSRC(8),CMSET(5)
      00159700
      DIMENSION STFWG1(E),EPSVEM(5),SSET(5)
      00159800
      DIMENSION EPMS(2),ES(2),SSIG(2),DEFL(2)
      00159900
      DIMENSION EPSSPM(8),CLEPTY(8)
      00160000
      DIMENSION OMCGSF(4),SGXALL(8)
      00160100
      DIMENSION CM(8),SIGW4(8),EPSVEM(8),EPSPT(8),STTIN(10,8)
      00160200
      DATA STFWGT/1..2..3..2..2..2..2..2..*/
      00160300
      00160400
      00160500
      00160600
      00160700
      00160800
      00160900
      00161000
      00161100
DO 4 J=1,8
NLOC(J)=1
IF(SIGA(J))SIGI(J,LT,0) BASCO(J)=EPSPM(J)
IF(ABS(SIGA(J))LT,ABS(SIGA2(J))) GC TO 4
NLOC(J)=2
NLSTC=1
4 CONTINUE
IF ALL STATES ELASTIC THEN DO ONE
IF(NPLSTC.EQ.0) GC TO 20
CALCULATE LOW LIMIT EST OF PLASTIC MEMORY INCREMENT
DO 5 J=1,8
DEPML(J)=0.
IF(NLOC(J).EQ.1) GC TO 6
EPSPM(J)=ABS(SIGA(J))
EPSPM(J)=ABS(SIGA(J))/E1(J)
DEPML(J)=EPSPM(J)-EPSPM(J)
DEPML(J)=SIGN(DEPML(J),SIGA(J))
DEPML(J)=DEPML(J)
5 CONTINUE
CALL ECLSM(SIGA,SIGA2,EPSTOT,EPSSRC,EPSPY,EPSEP)
CALCULATE UPPER LIMIT ESTIMATE OF PLASTIC MEMORY INCREMENT
DO 6 J=1,8
DEPML(J)=0.
IF(NLOC(J).EQ.1) GC TO 6
EPSPM(J)=ABS(SIGA(J))
EPSPM(J)=ABS(SIGA(J))/E2(J)
DEPML(J)=EPSPM(J)-EPSPM(J)
DEPML(J)=SIGN(DEPML(J),SIGA(J))
DEPML(J)=DEPML(J)
6 CONTINUE
EST CEL EPSEP
DEPML(J)=DEPML(J)
EST NUMBER OF ITER FOR EQUIL ACCURACY
CONPAC=ABS(DEPML(J)-DEPML(J))/2.
INDEX=INT(LGC(CONPAC)/ALN2)+1.
IF(INDEX.GT.NITER) NITER=INDEX
7 CONTINUE
IF(NITE.EQ.50) GC TO 15
DO 7 J=1,NITER
CALL ECLSM(SIGA,SIGA2,EPSTOT,EPSSRC,EPSPY,EPSEP,
1 DEPML,E1,E2,SIGA,BASCO,EPBN)
DO 7 J=1,8
IF(NLOC(J).EQ.1) GC TO 7
IF(SIGA(J))SIGI(J,LT,ABS(SIGA2(J))) DEPML(J)=DEPML(J)
IF(SIGA(J))LT,ABS(SIGA2(J))) DEPML(J)=DEPML(J)
DEPML(J)=DEPML(J)
7 CONTINUE
20 CONTINUE
FAILURE MODES
1=STRESS(TENSILE ONLY)
2=STRAIN(TENSILE ONLY)
3=STRAIN(TENSILE ONLY)
4=BIASTM(Rw(69)=EW(69))=Rw(60)/Rw(59)
UPDATE INSTANTEOUS COMPONENT OF wCRK(CR STRAIN(1W27)=3))
DO 22 J=1,4
DELETT(J)=EPSTOT(J)-EPSI(J)
IF(CLETT(J).LT.0.) GC TO 33
EX(w(210+J))+EX(w(210+J)+SIGA(J),BIASTM) +DELETT(J)
EX(1W27),EQ.3) EX(w(210+J)=EX(w(210+J)+CLELETT(J)
00167200
00167200
00167400
00167500
00167600
00167700
00167800
00167900
00168000
00168100
00168200
00168300
00168400
00168500
00168600
00168700
00168800
00168900
00169000
00169100
00169200
00169300
00169400
00169500
00169600
00169700
00169800
00169900
00170000
00170100
00170200
00170300
00170400
00170500
00170600
00170700
00170800
00170900
00171000
00171100
00171200
00171300
00171400
00171500
00171600
00171700
00171800
00171900
00172000
00172100
00172200
00172300
00172400
00172500
00172600
00172700
00172800
00172900
00173000
00173100
UPDATE
CD 8 J=1,8
RM(60+J)=SIGMA(J)
RM(70+J)=EPSCT(J)
PLASTIC MEMORY
EPSPER(J)=EPSPER(J)+ABS(DEPMUL(J)-DEPMLL(J))/2.
EPSPEP(J)=EPSPEP(J)+EPSPER(J)
RM(60+J)=EPSPEP(J)
VMSGMA(J)=SIGMA(J)
8 CONTINUE
CALL VISCP(EPSVP,CM,VMSGMA,RW,EL,CRPMA,BIASOM)
DO CALCULATIONS FOR CCST FUNCTION
RESIDUAL STRESS
IF(RM(25).LT.99.) GO TO 32
RM(34)=0.
DO 23 J=1,E
RM(34)=RM(34)+STRWGl(J)*ABS(SIGMA(J))
23 CONTINUE
SET
RM(35)=C.
DO 34 J=1,E
RM(35)=RM(35)+STRWGl(J)*ABS(EPSPEP(J))
34 CONTINUE
32 CONTINUE
NORMAL OUTPUT
IF(IW(15).EQ.1) GC TC 14
IF(IW(10).EQ.1) GC TO 14
GC TO 999
14 CONTINUE
SNAPBACK AND SET
DO 9 K=1,E
EPSNEK=0.
SETK=1.
EPSNECD=0.
SETD=0.
MK=1
NK=4
IF(K.EQ.1) GO TO 11
MK=4
NK=5
IF(K.EQ.2) GC TO 11
MK=6
NK=6
IF(K.EQ.3) GC TO 11
MK=6
NK=7
IF(K.EQ.4) GC TO 11
MK=7
NK=8
TO CALCULATE TOTAL SNAPBACK STRAIN USE STIFFER 5 VALUE (I.E.,
DON'T INCLUDE CREEP RECOVERY)
11 CONTINUE
SDTSTP=80.*(RM(24)-90.)*RM(30)
GC 12 J=MK
EPSPEP(J)=EPSSTP(J)+SIGMA(J)/STIFF(CM(J),SBTEMP)
12 CONTINUE
GO 10 J=M,N
EPBACN=EPBACN+(EPSRC(J)+EPSVM(J)+EPSSE(J))
1 E1(J)*STRWT(J)/RW(69)
SETx=SETx+(EPSVM(J)+EPSPM(J))*E1(J)*STRWT(J)
EPBACN=EPBACC+E1(J)*STRWT(J)/RW(65)
SETO=SETO+E1(J)*STRWT(J)
10 CONTINUE
EPBACN=EPBACN/EPBACC
SETO=SETO/SETO
EPSSE(K)=EPSSE=EPSAC
SETO=SETO
9 CONTINUE
RMS(75)=EPSPM(1)
RMS(30)=EPSSM(5)
DEFLATION
CETERMINE MOMENT BASED ON VALUES +0.5 INCHES IN FROM SLICE EDGES
THIS IN EFFECT FILTERS THE RESPONSE
(SEE P:SN16/ESE=7)
DO 26 K=1,2
IF(K.NE.1) GO TO 26
EPSM(1)=EPSSM(2)+EPSPM(1)+EPSPM(2)
EPSM(2)=EPSSM(2)+EPSPM(4)+EPSPM(4)
ES(1)=EI(2)
ES(2)=EI(4)
26 CONTINUE
EPSM(1)=EPSM(7)+EPSPM(7)+EPSPM(7)
EPSM(2)=EPSM(8)+EPSPM(8)+EPSPM(8)
ES(1)=EI(7)
ES(2)=EI(8)
27 CONTINUE
AVGIE=0
EPSNS=0
DC 28 J=1,2
EPSNS=EPSNS+ES(J)*EPSM(J)
AVGIE=AVGIE+ES(J)
28 CONTINUE
EPSNS=EPSNS/AVGIE
DO 29 J=1,2
SSIG(J)=(EPSNS-EPSM(J))*ES(J)
29 CONTINUE
SSIGN=ABS(SSIGN)+ABS(SSIGN)
ASSLWE(ISLIFIC W=EPSF(1)=1/3,L=4,5)
DEFL(K)=SIGM(60,75*SSIGN*AVGJE,SSIGN(1))
DEFLATION FOR THE FRACT TEST
FW(263*K)=DEFL(K)
25 CONTINUE
41 CONTINUE
5HEL=CCRE *WEIGHTING
DC 42 K=1,2
EPBACN=0
EPBACD=0
L=1
DIV=2.
IF(K.NE.1) GO TO 43
1=4
L=5
GC TO 45
43 CONTINUE
1=6
=7

S1 CONTINUE
DETERMINE EMC
    RW(23)=0.
    CuTSCIDE LCCP DOES SUMMATION
    DO 1=1,1w(11)
        PROC=1.
    INSCIDE LCCP DOES PRDCUCT
    DO 2=1,1w(11)
        IF(I.EQ.K) GC TO 2
        PROC=PROC*(RW(23)-RW(120+1)/(RW(120+K)-RW(120+1))
    2 CONTINUE
    RW(23)=RW(23)*PROC*L(K)
    1 CONTINUE
        IF(RW(23)GT.RW(18)) RW(23)=RW(18)
        IF(RW(23)LT.RW(17)) RW(23)=RW(17)
    DETERMINE TEMPERATURE
    RW(24)=0.
    FIRST TEST TO SEE IF IN WARK THRU PERIOD
    IF(RW(25).GE.RW(161)) GO TO 511
    RW(24)=90.*RW(25)*(U(1W(11)+1)-90.)/RW(161)
    GO TO 512
511 CONTINUE
    DO 3=1,1w(11)
        PROC=1.
    DO 4=1,1w(11)
        IF(I.EQ.K) GC TO 4
    4 CONTINUE
        RW(24)=RW(24)*PROC*L(K+1W(11))
    3 CONTINUE
512 CONTINUE
        IF(RW(24)GT.RW(2)) RW(24)=RW(2)
        IF(RW(24)LT.RW(19)) RW(24)=RW(19)
    GO TO 969
52 CONTINUE
STEP INPUT OPTION (BASED ON TIME)
    DO 21=1,1W(11)
        IF(RW(25).GE.RW(120+J)-RW(37)/2.) RW(23)=U(J)
        RW(24)=U(1W(11)+1)
    21 CONTINUE
    GC TC 969
53 CONTINUE
STEP INPUT BASED ON CM AVG
    DO 22=1,1W(11)
        IF(RW(45).LT.(RW(120+J)+1.) RW(23)=U(J)
        IF(RW(45).LT.(RW(160+J)+1.) RW(24)=U(1W(11)+J)
    22 CONTINUE
    GC TO 999
54 CONTINUE
TIME POLYNOMIAL SCHEDULE GENERATION
    FRM=RW(25)/100.
    RW(23)=U(1)
    RW(24)=U(1W(11)+1)
    DC 541 1=2,1W(11)
    RW(23)=RW(23)*U(J)*(PTRM**J-1)
    RW(24)=RW(24)*U(1W(11)+J)*(PTRM**J-1)
541 CONTINUE
    GC TO 999
200 CONTINUE
FUNCTION SIGEL(CM, THETA)
DIMENSION ETA1(6), ETA2(3)
DATA BETAN/1047552,-3.3253,-13.5366,6430,
1 -1.5658100000/ DATA BETAN2/-23.923.748,.0025/
ELSE Y(CM, THETA, ETA1, ETA2)
SIGEL = ELSE
999 RETURN
END

FUNCTION SIGMAX(CM, THETA)
DIMENSION ETA1(6), ETA2(3)
DATA BETAN/716.765,3.876.141.5336.58476,
1 -1.47632.04933/ DATA BETAN2/-14.04,64660263/
TCPSMN = Y(CM, THETA, ETA1, ETA2)
SIGMAX = TCPSMN
999 RETURN
END

FUNCTION EPSMAX(CM, THETA)
DIMENSION ETA1(6), ETA2(3)
DATA BETAN/-247.197.27612.217310.1188,
1 -0.4016/.00464/ DATA BETAN2/26.936.6400026/
EPSMAX = Y(CM, THETA, ETA1, ETA2)
999 RETURN
END

SUBROUTINE CST(L, RW, IN)
DIMENSION U(1501), RW(300), IN(100), SIGMAM(3),
1 STRDIF(3)
DATA FILE 1

CCST COMPONENTS:
1. COST TO GO=ENERGY
2. FINAL TIME
3. CONC MOISTURE
4. RESIDUAL STRESS
5. SET
6. FAILURES
MECHANICAL PARAM O-E TAKEN INTO ACCOUNT BY MAXIMUM
MOISTURE STRESS DIFFERENCE

COST 1 = ENERGY EXPENDITURE

RX(31) = RX(31) + (RX(24) - 90) = RX(37)
CALCULATE PERCENT LCAC FAILURE AS YOU GC
SEE SUBROUTINE STRESS FOR UPDATE CF RW(22)

IF(SW(9),NE,1) GC TO 999

NEW TERMINAL COSTS
FIRST STRESS TO ROOM TEMPERATURE AND RECAL STRESSES
FTHETA=RW(24)
RW(24)=PO
TFIN=RW(25)
RW(25)=INT
CALL STRESS(RW,IN)
RW(24)=FTHETA
RW(25)=FIN
NOW CALCULATE TOTAL COST
SW(1J)(3)=F
1. TOTAL ENERGY EXPENDED
U(IW(1))=U(IW(3))*FW(1)*RW(21)
2. FINAL TIME
RW(21)=FIN
3. CONC MOISTURE
RW(21)=TARGET
CMISS IS DISTANCE SHELL-CORE CONC FROM TARGET
CMISS=(RW(21)-RW(4))**2*(RW(21)-RW(4))**2
RW(33)=CMISS
U(IW(3))=U(IW(3))*RW(33)**2
4. RESIDUAL STRESS
SEE STRESS FOR RW(32)
U(IW(3))=U(IW(3))*RW(32)**2
5. SET
SEE STRESS FOR RW(39)
U(IW(3))=U(IW(3))*RW(39)**2
6. FAILURES
FOR RW(32) SEE STRESS
RW(32)=RW(22)
U(IW(3))=U(IW(3))*RW(6)**2
999 RETURN
END

FUNCTION STIFF(CM,TTHETA)
CIMJESI6N BETA1(6),BETA2(3),FAC(S)
DATA BETA1(1) .144J22,.5692,.4012,.2496.
1. -05704,.00292/
DATA BETA2/4.66,.283,.0013/
THIS SUBROUTINE CALCULATES STIFFNESS FOR TANGENTIAL
BOARDS ONLY. REFERENCE YCUNGS' TABLE 4 AND GRAPHS
CALCULATE EFFECTIVE CM FOR PURPOSES OF PLUGGING INTO
REGRESSION FORMULA(YCUNGS)
ELAST=CM,TTHETA,BETA1,BETA2)
STIFF=ELAST/1000.
999 RETURN
END

FUNCTION Y(CM,TTHETA,BETA1,BETA2)
DIMENSION BETA1(6),BETA2(3),FAC(S)
CALCULATE REGRESSION FROM YCUNGS' TABLE 4
CALCULATE EFFECTIVE CM
DO 12 J=1,11
PRED(J)=FLCAT(NPPTS)
12 CONTINUE
J=1
DO 4 I=1,260
HTVAR(I)=HTAG(J)
IF(J,GE,26) J=J-26
J=J+1
4 CONTINUE
MODEL PREDICTION HAS BEEN READ IN
CLOSE(UNIT=1,FILE="MDCLT,F.DAT")
17 CONTINUE
WRITE(INTERM,102) NPSTS
102 FORMAT(1X,12,3X,*PREDICTED POINTS READ*)
READ IN DATA
NPSTS=0
NTVAR=0
WRITE(INTERM,130) NBELL
130 FORMAT(1X,1,*DO YOU WISH TO READ DATA FROM FILE INPLT.DAT??)
READ(INTERM,131) NAMS
131 FORMAT(A1)
IF(NAMS,NE,='Y') GC TC 18
OPEN(UNIT=1,FILE="INPLT.DAT")
READ(1,FILE*) NPSTS,NTVAR
DO 11 J=1,NTVAR
DATA(1,J)=FLCAT(NPSTS)
11 CONTINUE
DC 5 I=1,ADPTS
READ(1,FILE*) (DATA(I+1,J),J=1,NTVAR)
5 CONTINUE
CLOSE(UNIT=1,FILE="INPLT.DAT")
18 CONTINUE
WRITE(INTERM,103) NTVAR,ADPTS
1O3 FORMAT(1X,13,3X,*DATA VARIABLES*,15,3X,*POINTS PER VARIABLE*)
6 CONTINUE
WRITE(INTERM,104) NBELL
104 FORMAT(1X,1,*PRED,DATA,VARLST,LELY,LEBX,LEBLL,SCALE,*,1)
READ(INTERM,105) NAMS
105 FORMAT(A5)
IF(NAMS,NE,='PRED') GO TO 201
IF(NAMS,NE,='DATA') GC TO 202
IF(NAMS,NE,='LELY') GO TO 203
IF(NAMS,NE,='LEBX') GC TO 204
IF(NAMS,NE,='LEBLL') GC TO 205
IF(NAMS,NE,='SCALE') GC TO 206
IF(NAMS,NE,='PRLT') GC TO 207
IF(NAMS,NE,='TGRLT') GC TO 208
IF(NAMS,NE,='VARLST') GC TO 209
IF(NAMS,NE,='CALCMF') GC TO 210
IF(NAMS,NE,='FIN') GO TO 555
WRITE(INTERM,106)
106 FORMAT(1X,*NAMS NOT RECOGNIZED*)
GO TO 6
201 CONTINUE
WRITE(INTERM,107)
107 FORMAT(1X,*TYPE INDEX OF INDEP PREDICTED VAR*)
READ(INTERM,109) PRCIV
WRITE(INTERM,110)
108 FORMAT(1X,*TYPE QUANTITY AND INDICES OF DEPVAR*)
BORDER
DC 4 K=1,101
IFGE(1,K)=
IFGE(101,K)=
IFGE(K,1)=
4 CONTINUE
AXES
DC 5 K=1,101
IYAXIS=INT((G1-XMIN)/(XMAX-XMIN))
IYAXIS=INT((G1-YMIN)/(YMAX-YMIN))
IF(IYAXIS,LT,1) GC TO 5
IF(IYAXIS,LT,101) GC TO 6
IF(IYAXIS,GT,1) GC TO 5
IF(IYAXIS,GT,101) GO TO 5
5 CONTINUE
NOW FLCT PREDICTED VARIABLES AND DATA POINTS
DC 6 J=1,NPRTD
DC 6 I=1,NPRTS
JINDEX=INT((100.*(FEDC(I,IPRSSIV)-XMIN)/(XMAX-XMIN))+1
JINDEX=INT((100.*(FEDC(I,IPRSSIV)-YMIN)/(YMAX-YMIN))+1
IF(JINDEX,LT,1) GC TO 6
IF(JINDEX,LT,101) GO TO 6
IF(JINDEX,GT,1) GC TO 6
IF(JINDEX,GT,101) GO TO 7
7 CONTINUE
X AXIS IS IN DIRECTION OF PAPER FEED
IFGE(JINDEX,JINDEX)=IPRSYM(J)
6 CONTINUE
NOW PUT THE DATA IN IMAGE
DC 6 J=1,NDATV
DC 6 K=1,NDATS
INDEX=INT((100.*(DATAV(J,1DADV)-XMIN)/(XMAX-XMIN))+1
INDEX=INT((100.*(DATAV(J,1DADV)-YMIN)/(YMAX-YMIN))+1
IF(INDEX,LT,1) GC TO 6
IF(INDEX,LT,101) GO TO 8
IF(INDEX,GT,1) GC TO 6
IF(INDEX,GT,101) GO TO 8
8 CONTINUE
IFGE(INDEX,JINDEX)=IDTSYM(J)
6 CONTINUE
EC ON THE GRAPH?
*PIE(INTERM,107)
107 FCMAT(1X,*TYPE CUT GRAPH?)
READ(INTERM,108) NANS
108 FCMAT(1X)
IF(NANS,NE,*YES*) GC TO 15
GO 14 I=1,101,2
15 CONTINUE
14 CONTINUE
WRITE(INTERM,109) (IFGE(I,J),J=1,101,2)
109 FCMAT(1X,*1A1)
14 CONTINUE
15 CONTINUE
WRITE(INTERM,110)
110 FCMAT(1X,*PRINT GRAPH?)
READ(INTERM,111) NANS
111 FCMAT(A2)
IF (NA15.EQ.,!NCAR) GC TC 999
12 CONTINUE
NOW PUT IMAGE IN THE FILE
OPEN (UNIT=1, FILE='PIC.DAT', ACCESS='APPEND')
WRITE (FILE,114)
114 FORMAT(/------------------------------------------------------------------)
CALL REWRITE(REW),IO,0,1,1)
NCAR='*'
WRITE (FILE,101) NCAR
101 FORMAT(A1)
NCAR='**'
WRITE (FILE,102) (LELTTL(J), J=1,50)
102 FORMAT(1X,50A1)
WRITE (FILE,112) XMIN,XMAX,YMIN,YMAX
112 FORMAT(1X,'INDEP VAR FRCM,*E13.4,3X,*TC',*E13.4)
   1 10X,'DEP VAR FRCM,*E13.4,3X,*TO',*E13.4/-----)
WRITE (FILE,103) (LBYAX(J), J=1,60)
103 FORMAT(66X,50A1/
DO 9 I=1,25
WRITE (FILE,104) NCAR, (IMGE(I,J), J=1,101)
104 FORMAT(11,5E1.10A1)
9 CONTINUE
DO 10 I=26,75
WRITE (FILE,105) NCAR, LELXAX(I-25), (IMGE(I,J), J=1,101)
105 FORMAT(A1,9X,A1,5X,10A1)
10 CONTINUE
DC II =76,101
WRITE (FILE,106) NCAR, IMGE(I,J), J=1,101
106 FORMAT(11,5E1.10A1)
11 CONTINUE
WRITE (FILE,114)
CLOSE (UNIT=1, FILE='PIC.DAT', ACCESS='APPEND')
999 RETURN
END
106 FCRTMAT(A1)
   IF(NAMS.EQ."*") GC TC 7
   IF(NAMS.EQ."*F") GC TO 559
   ELSE
      GO TO 6
   7 CONTINUE
   #WRITE(INTERM.*11)
111 FORMAT(I8) TYPE GRAPhICS OPTION/*
   1 1X,'1=DISK ONLY FCR20.DAT*/
   2 1X,'2=TERMINAL ONLY*/
   3 1X,'3=BCUV*/
   READ(INTERM.*) IN(21)
   CALL INITI(Ix(22))
   CALL BINIT?
   IOTYPE=ITY*/
   IF(IN(25).EQ.1) IOTYPE='FILE'
   IF(IN(25).EQ.3) IOTYPE='BCUV'
   CALL CUTMC(IOTYPE=20)
   CALL DLINX(XMIN,XMAX)
   CALL DLNX(YMIN,YMAX)
   CALL CHECK(LINX,MLNY)
   CALL CSFLAY(LINX,MLNY)
   PLOT SCATTER DATA
   CALL LINE(-4)
   DO 1 J=1,NDT

   CALL SYMBOL(NSYM)
   DC 2 I=1,NCPTS+1
   XVAR(I)=DATA(I,1,IDATIV)
   YVAR(I)=DATA(I,1,IDATDV(J))
   2 CONTINUE
   CALL CPLCT(XVAR,YVAR)
   1 CONTINUE
   PLOT MODEL PREDICTIO
   CALL LINE(0)
   CALL SYMBOL(0)
   DC 3 J=1,NPREDV
   DO 4 I=1,NCPTS+1
   XVAR(I)=PRED1(I,PREDIV)
   YVAR(I)=PRED1(I,PREDV(J))
   4 CONTINUE
   CALL CPLCT(XVAR,YVAR)
   3 CONTINUE
   PLOT THE LABELS
   CALL MOVABE(IXTTL,ITYTL)
   CALL LABEL(S0+ATITLE)
   CALL MCVAR(IYXY,IXYAX)
   CALL LABEL(S0+XLABEL)
   CALL MCVAR(IYXY,IIYAX)
   CALL LABEL(S0+YLABEL)
   CALL ANMCDE
   CALL HOME
   READ(INTERM.*) NAMS
   CALL ERASE
   #WRITE(INTERM.*107)
107 FORMAT(I8) TYPE LCVE LABELS?*
   #READ(INTERM.*108) NAMS
108 FORMAT(A1)
   IF(NAMS.EQ."*Y") GO TO 6
555 RETURN
END

END
VERSION 1
SUBROUTINE CALCME(RM,IN)

CCWCHX/FLY/FLY2(201,11)*CATA(100,10)+IMAGE(101,101),
1 LBLXAX(50),LBYAX(50),LALTTL(50),NTVAR(201),NTAG(26),
2 HPROD,VPROD(11),VPROD,NXNTCV,IXNTCV(10),NXNTCV,
3 NPRTS,NXPTS,NCTVAR,XXMIN,XXMAX,YYMIN,YYMAX,XXLMX(5),XXLMY(5)
DIMENSION RM(300),IN(100)
THIS SUBROUTINE SETS UP FILES TO BE READ BY SPIDER'S
GRAPHICS SOFTWARE
DATA IFILE,INTERM/1,5/
DATA ZEROL/0,1/
PLCT AXES
OPEN(UNIT=1,MODE='IMAGE',FILE='XAX.DAT')
NXPTS=2
WRITE(FILE) NXPTS,XMIN,ZERO,XMAX,ZERO
CLOSE(UNIT=1,MODE='IMAGE',FILE='YAX.DAT')
OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
NXPTS=2
WRITE(FILE) NXPTS,ZERO,YMIN,ZERO,YMAX
CLOSE(UNIT=1,MODE='IMAGE',FILE='YAX.DAT')
DO 1 J=1,NXPTS
GC TO (201,202,203,204,205,206,207,208,209,210),J
2 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GO TO 211
201 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GO TO 211
202 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GO TO 211
203 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GO TO 211
204 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GO TO 211
205 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 211
206 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GO TO 211
207 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GO TO 211
208 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 211
209 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 211
210 OPEN(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 211
CONTINUE
WRITE(FILE) NXPTS,((DATA(1,IDATIV)),
1 CAT(1,IDATIV(1)),I=2,NXPTS+1)
GO TO (301,302,303,304,305,306,307,308,309,310),J
301 CLOSE(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GO TO 211
302 CLOSE(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 311
303 CLOSE(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 311
304 CLOSE(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 311
305 CLOSE(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 311
306 CLOSE(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 311
307 CLOSE(UNIT=1,MODE='IMAGE',FILE='XBD.DAT')
GC TO 311
103 FORMAT('FINISHED RUN CCGRF')
559 RETURN
END