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Robert L. Little
Major Professor

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DEVELOPING AND EVALUATING CONTINUOUSLY CHANGING SCHEDULES FOR HARDWOOD LUMBER DRY KILNS

A Thesis

Presented for the

Master of Science

Degree

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Richard L. Toennisson

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ABSTRACT

Two methods for designing continuously changing hardwood dry kiln schedules were developed. A continuously changing mini step drying schedule for 4/4 red oak was successfully designed and adapted to a micro computer. The demonstration trials were successfully completed. Comparison with a conventional step schedule trial shows the designed midpoint schedule performed as expected taking 11 percent longer but using 5.1 percent less energy.

A second method for designing continuously changing hardwood dry kiln schedules using equations was developed. Equations using percent moisture content to predict dry bulb or wet bulb depression temperatures were found for 8 dry bulb and 9 wet bulb depression schedules.

An evaluation of continuously changing hardwood dry kiln schedules indicates an estimated 6.5 percent savings in energy. Energy and time savings result in a 3.8 year pay back period for the investment of computer equipment.

PREFACE

In 1982, the University of Tennessee, supported by the Tennessee Valley Authority, initiated a program to improve the efficiency of conventional hardwood lumber dry kilns. The first step in this program, completed in 1985, was to investigate and assemble a system to gather data from and control a small experimental kiln owned by the University. By using a small computer to continuously monitor and control the kiln, large amounts of data could be collected and analyzed. This empirical data is vital to future research in drying improvement.

This dry kiln study system is being used by the University of Tennessee and the Tennessee Valley Authority for a series of studies and demonstrations to improve the operation of conventional hardwood dry kilns. This study and thesis is an effort toward that end.

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LIST OF ABBREVIATIONS

Thousand Board Feet (MBF)

Board Feet (BF)

Continuously Changing Schedule (CCS)

Continuously Rising Temperature (CRT)

Wet Bulb Depression (WBD)

Moisture Content (MC)

Fiber Saturation Point (FSP)

Forest Products Laboratory (FPL)

Dry Bulb (DB)

Wet Bulb (WB)

Equilibrium Moisture Content (EMC)

Resistance Temperature Detector (RTD)

British Thermal Unit (Btu)

CHAPTER I

LUMBER DRYING AND EQUIPMENT

Introduction

Computerized hardwood lumber dry kiln control systems are starting to replace older pneumatic controlled recorders. Improved drying schedules to complement the computer controllers have yet to be developed. Newer, more efficient, schedules are needed to modify the standard temperature step schedules. The development of continuously changing schedules (CCS) for use in the computerized control system of a dry kiln may be possible. CCS may yield cost savings through reduced lumber degrade, energy consumption, and drying time. This paper investigates the effectiveness of CCS and proposes a mathematical method by which conventional hardwood schedules may be converted to CCS.

Review of How Wood Dries

A standing tree, depending on species, may have more than half its live weight in the form of sap (water with a diluted solution of sugars). Before wood can be used for most products this moisture must be removed.

Wood will lose or pick up water depending on the surrounding environment. Sapwood dries fastest, but usually has a higher initial moisture content than heartwood. Given enough time, lumber will lose moisture until it reaches the equilibrium moisture content (EMC) of the surrounding air.

As wood dries below the fiber saturation point (FSP), it will begin to shrink. The amount of shrinkage is anisotropic, predictable depending on grain direction. It is greatest across the grain (flat sawn or tangential), up to half as much in the direction of the rays (quarter sawn or radial), and least along the grain (longitudinal).

Wood dries from the outside inward. Water, in liquid or vapor form, moves to the surface of wood by diffusion or mass flow. Here it is evaporated into the surrounding atmosphere. The movement of moisture through the wood results in variable moisture contents across the width of a board. This moisture gradient of drying wood can be as great as 60 percent moisture content, it is highest in the center of a board and decreases in the direction of the surface (Bois, 1977).

Stresses develop in the wood during drying. As the outside shell of lumber dries below FSP, it starts to shrink. The inside, however, is still too wet to shrink. This phenomenon is one of the major causes of drying defects (checks). Lumber dry kilns and schedules which control the speed of drying are used to keep these defects at acceptable levels.

Review of Lumber Drying Equipment

Conventional lumber kilns are the most popular means of drying hardwood lumber in the United States. Conventional kilns are large insulated buildings equipped with a heat source (steam or direct), a humidification system (usually steam), vents, and fans to circulate air. Inside a conventional kiln lumber is stacked on stickers (small strips of wood) to allow air circulation.

Monitoring of moisture content in a conventional kiln typically uses a sampling method based on the ovendry weights of representative samples. In a commonly used method described by Rasmussen (1961), one sample is taken for about every 10 MBF. Each 2 foot long sample is taken from boards selected to represent the moisture content variation and drying difficulty of lumber. Small wafers are cut from each end of the samples, weighed, and oven dried to establish green and dry moisture contents. These calculated moisture contents are assumed to be those of the larger sample. Finally, the large sample is weighed and returned to the lumber pack. As drying progresses, these samples are periodically retrieved and weighed to find current moisture contents. The operator uses these moisture contents to establish kiln conditions. The success of this method depends heavily on the skill of the operator to select representative samples and correctly interpret the results.

Conventional dry kilns are operated by recorder-controllers. A controller compares kiln chamber wet and dry bulb temperatures (as measured by gas filled bulbs or RTD) to desired levels (set points) and makes needed adjustments to maintain the preset conditions. Given the conservative nature of the forest products industry and a 20 year plus working life, conventional dry kilns may remain the mainstay of hardwood drying for some time.

Occasionally, new methods in drying are developed and accepted by the forest products industry. High temperature drying, for example, revolutionized the drying of southern pine structural lumber. Some

important improvements in conventional drying, such as variable speed fans and automatic controls, are only now being recognized.

Several innovative drying methods have made inroads into conventional drying. Dehumidification drying units made their debut in the mid 70s and have proven useful for some segments of the forest products industry. The use of microwave energy for commercial lumber drying is also receiving some attention (Southern Lumberman, 1987).

Water Removal. The most common method of wood moisture removal in commercial lumber dryers is air transfer. The heat energy in air is used to evaporate moisture from the wood. The air transportation method is used in conventional, predrying, air, dehumidification, and solar drying systems.

Other wood drying methods include vacuum, chemical, and microwave. Energy and moisture in these methods are transported in ways different from conventional drying. The major methods of drying lumber and equipment types are listed in Table I-1.

Review of Literature and Past Accomplishments

Most conventional hardwood kiln schedules consist of a series of long steps at constant temperatures (Figure I-1). Drying conditions are changed when the moisture content of the sample indicate the lumber can be safely dried at a faster rate. Many sampling techniques are conservative. As a result, some lumber may not be drying at its optimum safe rate, especially toward the end of schedule. A schedule using constantly increasing, or small step increases in temperature would have

Table I-1. Lumber Drying Methods

Drying System	Heat Transfer and Moisture Removal Medium	Attributes
Air Drying	Unconditioned and unheated air.	Inexpensive but weather dependent. Commonly used.
Fan Sheds	Unconditioned and unheated air.	Protected but weather dependent. Oaks are difficult.
Solar Kilns	Unconditioned and variable heated air.	Finish dry small quantities. Weather dependent.
Predryers	Unconditioned and steam heated air.	Low temperatures with large rotating lumber volume.
Low Temperature Kilns	Conditioned and steam heated air.	Low temperature schedules for northern predrying.
Conventional Kilns	Conditioned and heated air from various fuels.	Schedule use finish drying from green, air dried or predried lumber, versitile.
High Temperature Kilns	Conditioned and heated air from various fuels.	Fast drying of construction lumber, temperature above 212 degrees Fahrenheit.
Dehumidification Kilns	Humidity and heat controlled by an electric condensor.	Finish drying from green or air dried. Generally slower than conventional.
Microwave Dryers	Waves supply heat air removes moisture.	Fast drying for sized dimension.
Micro/Vacuum Dryers	Waves supply heat vacuum removes water.	Fast drying for thick dimension. Equipment is complex and expensive.
High Pressure Steam Cylinders	Steam supply heat, makes vacuum.	Fast drying of construction lumber. Convenient when treating.
Chemical Drying Pressure Treated	Solution supply heat and remove water.	Fast drying when treating ties posts and poles.
Jet Drying	High velocity heated air removes water.	Fast drying for veneer. Experimental for lumber.
Press Drying	Metal plates supply heat and stability.	Accelerated drying for some species and types of products.

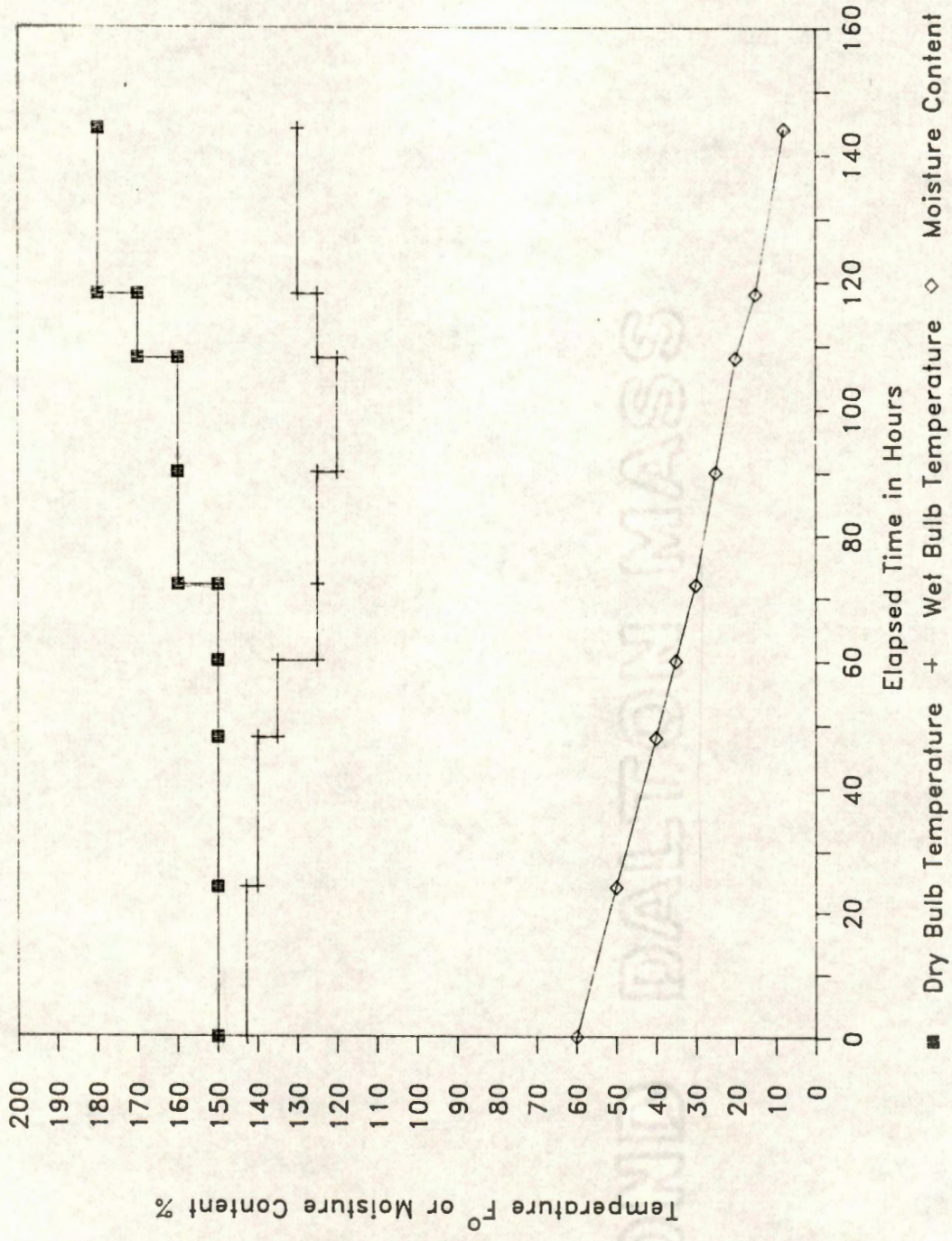


Figure I-1. Conventional Hardwood Schedule

the advantage of always drying at the fastest, safest rate for each set of kiln conditions.

Continuously rising temperatures (CRT) have been proposed as a method to increase dry kiln efficiency. The basic theory behind CRT is that moisture escapes from wood continuously, at changing rates. At constant temperature, these rates decrease with decreasing moisture content.

Resch and Ecklund (1966) experimented with CRT for drying 4/4 redwood, using a cam-operated controller. A cam-operated controller consists of a metal cylinder of various diameters (cam) installed on a clock device. The clock presents each cam diameter in turn to the controller. The controller actuates temperature settings in proportion to the cam diameters. These controllers were successful in controlling the kiln which resulted in a 9 percent decrease in drying time over conventional controllers and schedules. Because the cam-controller is based on a time schedule rather than on the moisture content of the drying lumber, it has limited use for hardwoods.

Dedrick (1969) described a process for CRT lumber drying, for which the Weyerhaeuser Company received a U.S. Patent (#3,404,464). The lumber drying rate was monitored and manipulated using an air-wood temperature gradient, where lower initial temperatures were used to reduce drying defects. Substantial decreases in drying time resulted.

Noffsinger (1978) further described the CRT process and its commercial use for western softwoods and limited use for maple and birch. Benefits of the CRT process were shorter schedules, improved

lumber quality, and fuel savings. Using CRT with conventional kilns requires temperature control equipment, humidity control techniques, and a predetermined program of dry bulb temperature rise. Fan reversals are not used. Large amounts of intake air are required to maintain large wet bulb depressions at lower drying temperatures. In other testing, it was suggested that since drying times vary with equipment, species, and other conditions, the ideal CRT rate of drying for every situation has not yet been established.

Automatically Controlled Dry Kilns

In 1971, Wengert and Evans designed and demonstrated an automatic dry kiln control for use on new or existing kilns. The control continually measured the wood moisture content, calculated using wood weight, via load cells, automatically determined the desired temperature settings, and proportionally opened and closed the vents and valves. A 10 percent decrease in drying time was achieved for green 4/4 northern red oak using a smoothed step conventional schedule.

A report by Metric and others (1974) explained the advantages of a computer controlled drying system. It recommended that a computer controlled system have three parts; (1) the control strategy model; (2) a simulation model of the wood drying process, and; (3) a remote sensing system for moisture, temperature and strain gradients. The proposed study was based on a strain gradient technique. The wood drying model has not yet developed.

Holmes and Arganbright (1976) repeated the computerized weight-actuated control system using an electrostatic control chart. Manual,

cam, and weight control systems were compared for ponderosa pine and white fir. Results showed a 24.2 percent drying time savings for ponderosa pine and a 13.2 percent savings for white fir. Problems included moisture condensation and mandatory temperature compensations in the load cells and electrical connections. A conventional step drying schedule was used.

Alexandrou (1980) completed a graduate thesis on the development of continuous change schedules. He defined the concept of "drying effort" to quantify families of linear drying schedules. He also described a method for developing CCS from step schedules. The experimental runs with a cam controlled kiln showed minor improvement in efficiency.

Alexandrou also described the families of drying schedules he worked with as maximum point, midpoint and minimum point schedules. A maximum point schedule is made by extending lines between the highest temperature points at a step schedules moisture content control points. In effect it proportionally increases the highest recommended temperatures from step point to step point. Minimum point schedules are similar but use the lowest temperatures. Midpoint schedules use points halfway in between the maximum and minimum. An example of these schedules relative to the step schedule they are derived from appears in Figure I-2. His work suggested that maximum point schedules may dry the fastest with a risk of drying defects, that minimum point schedules may dry the slowest with the least defects and energy use, and that the midpoint schedules may have a mixture of both of the previous schedules attributes.

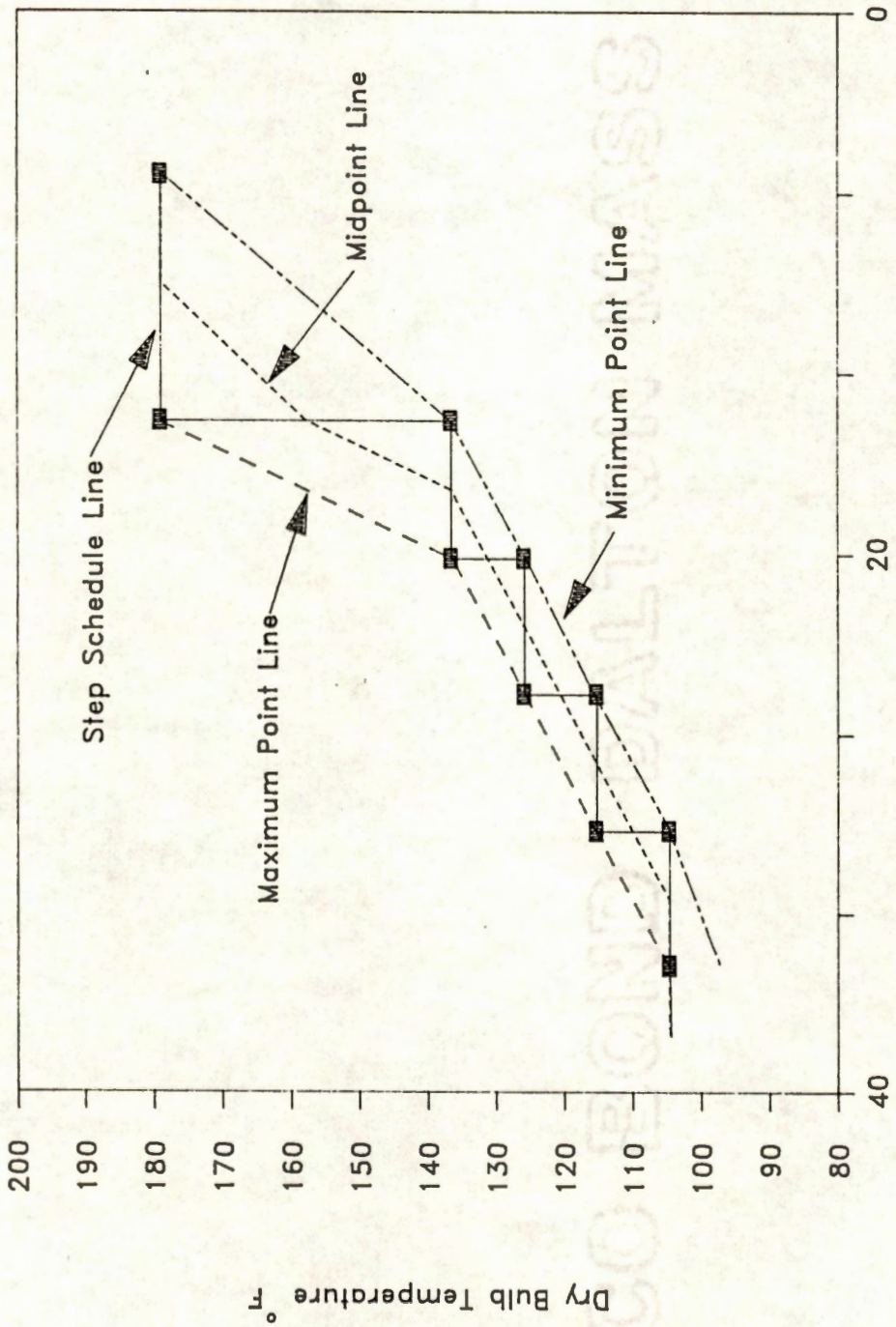


Figure I-2. Examples of Maximum Point, Midpoint, and Minimum Point Drying Schedules

Little, Moschler, and Toennisson (1986) retrofitted a small kiln with a computer controller and load cells to demonstrate the use of commercially available equipment. The computer maintained and used a library of stored step schedules on demand. The equipment testing runs were successful and suggest that low-cost computer based control systems may be feasible for retrofitting existing commercial kilns.

Industry acceptance of automatic control devices for commercial hardwood drying operations has been slow. It should be noted that during the 1970s and early 1980s several domestic and international manufacturers marketed kiln control products similar to those described in the literature. They vary in complexity depending on controlling functions and manufacturers. All but one commercial system used electrical resistant moisture detection as the primary wood moisture monitoring technique. However, these installations, have yet to reach their full potential. Because a shortage of information on effective drying schedules for automatic control devices still exists.

Objectives

A continuously changing schedule is the next a logical next step in hardwood dry kiln schedule development, and could maximize the value of computerized control systems. This thesis proposes to develop and test continuously changing hardwood drying schedules.

The objectives of this study were:

1. Design a method for the development of CCS for eastern hardwoods;

2. Estimate the economic potential of CCS for 4/4 Red Oak lumber; and

3. Demonstrate the use of CCS with a computerized controller for 4/4 Red Oak lumber.

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CHAPTER II

ECONOMIC ANALYSIS OF A CONTINUOUSLY CHANGING SCHEDULE

Commercial lumber drying is a controlled procedure which processes large amounts of lumber requiring relatively large amounts of energy. Nearly five billion board feet of hardwood lumber is kiln dried in the United States every year. Approximately 70 percent of the energy used to convert loss into finished products is concentrated in lumber drying, amounting to 1.43×10^{16} Btus per year (Comstock, 1975).

The literature suggests that automatically controlled kilns and continuously changing drying schedules could have savings in energy and time (Wengert, 1971). A savings in either could have a positive effect on the economies of drying lumber.

To study the economic potential of CCS the energy use and drying times of a conventional schedule and a CCS were compared. 4/4 Red Oak was used because it is in common commercial use. There are two parts to the analysis, first an estimate of the energy use and then an overall cost savings including time.

Energy Savings

Potential energy savings are calculated by estimating dry kiln energy use. Estimates of total energy consumption are composed of several components, each component representing a different type of energy consumption. The monetary value of any savings is calculated

based on the use of natural gas for fuel value at 5.50 dollars per thousand cubic feet.

Energy Use

Energy use values are calculated based on a procedure developed by Shottaffer and Schuler (1974). This procedure was modified and computerized by Toennisson (1981). Energy use values computed by this program are estimates calculated under controlled conditions. The principal value of the program is in comparing the effects of different variables on energy consumption. Energy use estimates computed by the program are for a free standing conventional kiln, exclusive of the efficiency of the heating or humidifying units.

Computations. Computations for kiln energy needs were separated into seven equations of energy use or steps. The computations for each energy estimation step were done separately for each step in the drying schedule. Results from each of the kiln schedule steps were summed by energy use to calculate the total energy consumption for the test case.

Step 1: Energy needed to raise the wood to kiln temperature.

$$H1 = ODW \times dT \times S \times TC \quad (2\text{-}1)$$

Where:

H1 = Energy to Raise Temperature of Wood in BTUs

ODW = Ovendry Weight of Lumber in Pounds

dT = Temperature Rise in Degrees Fahrenheit

S = Specific Gravity of the Wood

TC = Thermal Capacity of Water in BTUs at this Temperature

Step 2: Energy needed to overcome hygroscopic forces.

$$H2 = ODW \times D \quad (2\text{-}2)$$

Where:

D = Heat of Desorbtion, in BTUs, for Moisture Content Change

Step 3: Energy needed to raise remaining water to temperature.

$$H3 = ODW \times MCI \times TC \times dT \quad (2\text{-}3)$$

Where:

MCI = Change in Wood Moisture Content in Percent

Step 4: Energy needed to evaporate the water.

$$H4 = W \times (dT + Lh) \quad (2\text{-}4)$$

Where:

W = Weight of the Evaporated Water in Pounds

Lh = Latent Heat of the Air in BTUs

Step 5: Energy needed to raise the kiln temperature and humidity.

$$H5 = Wv \times (Sha \times dT) \quad (2\text{-}5)$$

Where:

Wv = Weight of the Vented Air in Pounds

Sha = Specific Heat of Air

Step 6: Energy needed to raise the kiln temperature between steps.

$$H6 = Wa \times ((dT \times Sha) + Lhi - Lho) \quad (2\text{-}6)$$

Where:

Wa = Weight of the Kiln Air in Pounds

Lho = Latent Heat of Outside Air in BTUs per Pound

Lhi = Latent Heat of Inside Air in BTUs per Pound

Step 7: Energy needed to replace system losses.

$$H7 = U \times A \times dT \times Th \quad (2\text{-}7)$$

Where:

U = Heat Transfer Coefficient of the Structure

A = Area of the Structure in Square Feet

Th = Time in Hours

Test cases. Two test cases are compared; the 4/4 red oak Forest Products Laboratory (FPL) drying schedule T4D2 and a CCS derived from T4D2 (Rasmussen, 1961). A prefabricated 60 MBF capacity hardwood kiln is assumed for both cases. Drying time (512 hours) and moisture contents (55% to 7%) for both cases are based on literature estimates (Rasmussen, 1961). Ambient air temperature is assumed to be 70 degrees Fahrenheit, and the absolute humidity is 0.001 pounds of water per pounds of dry air. Other assumptions are shown in Table II-1.

Energy estimates. The dry kiln energy use model indicates a significant energy savings with the use of the CCS derived from T4D2 (Table II-2). A 6.5 percent energy savings resulted when using the

Table II-1. Construction Material and Dimensions of Hypothetical Dry Kiln

Insulation Values, "U" Factor, BTUs per Hour per Square Feet for Total Thickness	
Prefab Kiln	"U"
Walls	.107
Roof	.107
Doors	.215
Floor	1.82

Kiln Capacity MBF	Feet			Number of 16'x4'x6' Packages
	Height	Width	Length	
60	24	26	44.5	36

Table II-2. Dry Kiln Energy Use Estimate for a 60 MBF Kiln Comparing a Step and a Continuously Changing Schedule

Component	Step		CCS	
	Million BTUs	Percent	Million BTUs	Percent
H1 - Heat Wood	6.04	3.8	6.04	4.1
H2 - Hygroscopic	3.00	2.0	3.00	2.0
H3 - Residual Water	1.13	0.7	0.48	0.3
H4 - Remove Water	83.72	53.0	83.72	56.6
H5 - Vent Losses	37.75	23.9	29.55	20.1
H6 - Heat Kiln	0.13	0.1	0.13	0.1
H7 - Kiln Losses	26.06	16.5	24.69	16.8
Total	157.80	100.0	147.61	100.0

continuous schedule. Table II-2 indicated that most of the energy savings were from vent losses which were reduced by 21.7 percent and contributed 5.2 percent of the total savings. The remaining 1.3 percent savings was contributed by the lower kiln building losses and less energy needed to increase the residual water temperature to the next step.

Time and Money Savings

The estimated 6.5 percent energy savings which results from a CCS could mean a savings of 9.3×10^{14} Btus per year when applied to the hardwood lumber industry. Using natural gas at a cost of 5.50 dollars per million Btus (one thousand cubic feet) the CCS could save an estimated 1.01 dollars per MBF of lumber dried.

Wengert (1971) described an estimated 10 percent drying time savings. A reduction in drying time would reduce required kiln capacity by the same amount. For an existing kiln this represents a 10 percent increase in production, or for a new kiln it reduces the needed capacity by the same amount. Either change could reduce the cost of drying lumber.

Investment and Energy Use

Costs or savings per MBF of lumber dried are commonly used measures of drying efficiency. Therefore, annual costs were used to compare the effects of CCS and the step schedule on energy and time savings in a commercial hardwood lumber drying operation.

The example assumes a commercial drying operation which processes 3,150 MBF of 4/4 red oak per year. The operation has three new 60 MBF capacity kilns which cost 2.50 dollars per board foot capacity to install. The kilns are fueled by natural gas at 5.50 dollars per thousand cubic feet. The interest rate is 10 percent and the equipment life is expected to be 10 years. Finally, the cost of the first computer controller is 12,500 dollars, each additional controller costs 7,500 dollars, and conventional controllers cost an estimated 2,500 dollars each.

Results show CCS with a process savings of 2.39 dollars per MBF (Table II-3) when compared to a step schedule. The CCS example dried an additional 348 MBF of lumber per year with the same kiln capacity reducing the CCS unit investment cost by 1.41 dollars per board foot. Combining the CCS energy and investment cost saving will result in a cost reduction of over 8,300 dollars per year. This would pay for the difference in the cost of conventional and computer controllers (20,000 dollars) in 3.8 years.

Table II-3. Investment and Energy Use Cost Comparison Step and Continuously Changing Schedules, 4/4 Green Red Oak

	Step Schedule	CCS
Energy Use per MBF	2.63 Million Btus	2.54 Million Btus
Drying Time in Days	21	18.9
MBF Dried per Year	3,150	3,478
Kiln Capacity in MBF	180	180
Kiln Investment	$442,705	$442,705
Controller Investment	$7,500	$27,500
Total Investment	$450,205	$470,205
Annual Value of Total	$73,269	$76,524
Energy Cost per MBF	$14.47	$13.48
Annual Cost per MBF	$23.41	$22.00
Total Costs per MBF	$37.87	$35.48

Summary of Savings

Savings per MBF	$2.39
Savings per Year	$8,312
Estimated Pay Out Time of $27,500 Full Value Controller (i=10%, simple)	5.2 Years
Estimated Pay Out Time of $20,000 Controller Value Difference (i=10%, simple)	3.8 Years

CHAPTER III

TESTING A CONTINUOUSLY CHANGING SCHEDULE

Discussion

Step Schedules

Step lumber drying schedules are the most common form of control for hardwood dry kilns. Step schedules are designed to maintain safe drying rates within the control limits of conventional dry kilns. Developed at the Forest Products Laboratory, step schedules have been in use for decades. These schedules are the current industry standard for hardwood kiln drying.

Step schedules were probably first derived as the older type progressive track kilns were modified to batch process. In progressive drying the lumber was moved though long kilns to drying stations. Each succeeding station had increasingly more severe drying conditions. When this became impractical because of increased material costs, the lumber was kept in one place and kiln conditions were altered. Schedules first reflected conditions of the old stations, but have since been modified.

Each step of a schedule consists of two temperatures. These are the dry bulb temperature (a measure of sensible kiln air temperature), and wet bulb temperature (a function of kiln air humidity). The difference between the two, in degrees, is the wet bulb depression (WBD). It is used as an indication of drying severity. The larger the depression, the faster and more severe the drying rate.

In general, a schedule has six to eight steps which gradually increase the WBD inside the kiln until all the liquid water (free water) is removed (fiber saturation point) from the wood. Then both temperature and WBD are increased to accelerate the removal of bound water in cell walls and fibers (Table III-1). Two types of drying schedules are in common use, time based and moisture content.

Time schedules. Time schedules are those which change kiln conditions based on time (Table III-2). In some cases the lumber being dried is so homogeneous and easy to dry that there is little need for extensive testing for moisture content and defects. The drying rate of this lumber is predictable and control temperature changes can be scheduled. Time schedules are primarily used for western softwoods.

Moisture content schedules. Moisture content schedules use wood moisture content levels to dictate step or temperature changes (Table III-1). Moisture content is commonly determined by a representative sampling technique. Perhaps dozens of two foot long samples must be removed from the kiln, weighed, recorded, and replaced. Moisture content schedules are often considered to be laborious by operators because of the sampling. In actuality, few operators take all of the sample readings and often set the kiln set points by experience. Step changes are only possible when an operator is on duty.

Automatic kiln control systems using load cells determine the moisture content by weighing all or part of the kiln charge. The control system uses this information to set kiln conditions. The

Table III-1. Step Schedule Controlled by Moisture Content for 4/4 Upland Red Oak, T4D2

Step number	Moisture content % at start of step	°F Dry Bulb temperature	°F Wet Bulb depression	°F Wet Bulb temperature
1	Above 50	110	4	106
2	50	110	5	105
3	40	110	8	102
4	35	110	14	96
5	30	120	30	90
6	25	130	40	90
7	20	140	45	95
8	15	180	50	130

Note: Equalization and conditioning steps are excluded.

Source: DRY KILN Operator's Manual

Table III-2. Time Schedule for 4/4 Douglas Fir, BS5-BK4

Time (hours)	°F Dry Bulb temperature	°F Wet Bulb depression	°F Wet Bulb temperature
0 - 12	135	7	128
12 - 24	135	7	128
24 - 36	140	10	130
36 - 48	140	10	130
48 - 60	145	15	130
60 - 72	145	15	130

Source: DRY KILN Operator's Manual

controller usually runs a step, or modified step schedule. The advantage of automatic kilns is that moisture content readings and temperature changes are made at any time, without operator input, and without entering the kiln.

CCS and Mini Steps

Continuously changing schedules can use either time or moisture content to determine temperature settings. There are several forms described in the literature review. Two new types described below show promise.

Mini step schedules. A mini step drying schedule has 20 to 50 small schedule changes, each based on moisture content. The schedule is designed to make changes at the threshold of operational accuracy levels of the dry kiln control equipment. For example, many conventional kiln controllers are operationally accurate to one degree because the equipment indicators can record nothing smaller. A mini step would have small steps with step changes no smaller than this tolerance. They would also be controlled by similar practical changes of moisture content. Therefore, from the perspective of the controller's resolution, these are almost continuously changing schedules.

Equation schedules. An equation controlled drying schedule is the true form of continuously changing hardwood dry kiln schedules. In this type of CCS, the drying curve and controlling temperature of the drying process are defined mathematically (Figure III-1). For example, if a moisture content could be mathematically related to desired kiln

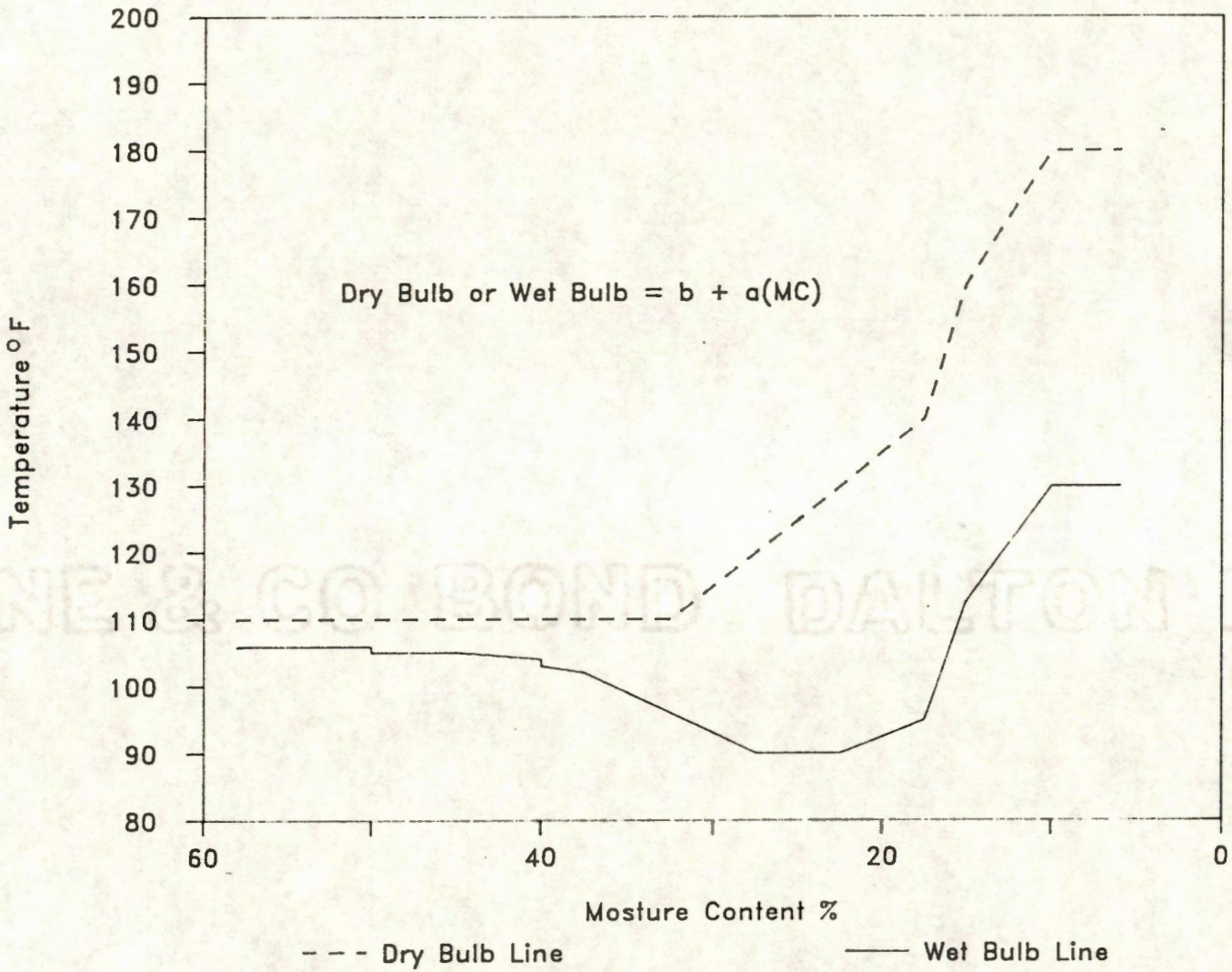


Figure III-1. Hardwood CCS Equations

conditions, a computer could control a kiln by reading a moisture content, solving for an unknown temperature, and setting the kiln conditions accordingly.

Testing Equipment

Dry kiln. The track loaded kiln used in this study is of prefabricated construction. It has a maximum capacity of approximately 725 board feet (4/4 basis). The kiln mimics a standard full sized commercial unit: air is circulated by fans through stickered lumber; the kiln is heated by steam coils; and humidity is controlled by steam spray or vents.

The kiln is equipped with a dual control system. The first is a standard on-off electrical RTD recorder with standard dry bulbs, and a wet bulb with a water sock. The other is a customized computer unit designed and installed by the University staff. It has load cells on the track supports and an in-kiln capacitance-admittance moisture detector system. Both systems use pneumatic signals to operate the spray and heat valves and the vents. In addition to the readings already mentioned, probes are installed to measure: ambient temperature and dew point; venting air flow and temperature; kiln air velocity and dew point; steam pressure, steam flow, and steam temperature and; usage of vents, heat, and spray. Recording of data by the computer continues independent of either control system.

Computer controller. The computer dry kiln recorder controller is based on a micro computer equipped with an analog to digital converter

board. All components and attachments are commercially available. This unit is designed as a prototype for retrofitting existing commercial kilns with computer controllers. Based on information from the load cells and the in-kiln moisture meter, the computer system controls the kiln according to the computer program KILN COMP written by Little (1985). Readings from the kiln and ambient air are averaged over 150 cycles (about 14 Minutes) and digitally recorded. Data storage for 30-day runs has approached 3/4 million bytes.

Drying Trials

Schedule Choice

The standard drying schedule T4D2 for 4/4 red oak (Table III-1) from the FPL was chosen for the conventional run. The schedule made for the CCS run is a ministep using T4D2 as a guide (Table III-3). Modeled on Alexandrou's classification, the mini step schedule is a "Midpoint Schedule" which should have an equal or longer drying time than the conventional step schedule (Figure III-2).

Work Plan

(1) Two similar charges of 4/4 red oak were dried in the experimental dry kiln at the University of Tennessee. The first charge, dried according to the conventional FPL schedule T4D2, was controlled manually by typical moisture samples taken once a day. Data from the run was recorded by the computer. The other charge used the computer control system and a midpoint CCS derived from (Figure III-3) T4D2. Data was also recorded by the computer.

Table III-3. Continuously Changing Mini Step Schedule for 4/4 Upland Red Oak

Step number	Moisture content % at start of step	Dry Bulb temperature °F	Wet Bulb depression °F	Wet Bulb temperature °F
1	Above 50	110	4	106
2	50	110	5	105
3	45	110	6	104
4	41	110	7	103
5	38	110	8	102
6	37	110	9	101
7	36	110	10	100
8	35	110	11	99
9	34	110	12	98
10	33	110	14	96
11	32	112	16	96
12	31	114	19	95
13	30	116	22	94
14	29	118	26	92
15	27	120	30	90
16	26	122	32	90
17	25	124	34	90
18	24	126	36	90
19	23	128	38	90
20	22	130	40	90

Table III-3. (Cont.)

Step number	Moisture content % at start of step	Dry Bulb temperature °F	Wet Bulb depression °F	Wet Bulb temperature °F
21	21	132	41	91
22	20	134	42	92
23	19	136	43	93
24	18	138	45	93
25	17	140	45	95
26	16	146	46	100
27	15	152	47	105
28	14	157	47	110
29	13	163	48	115
30	12	169	49	120
31	11	174	49	125
32	10	180	50	130

Note: Equalization and conditioning steps are excluded.

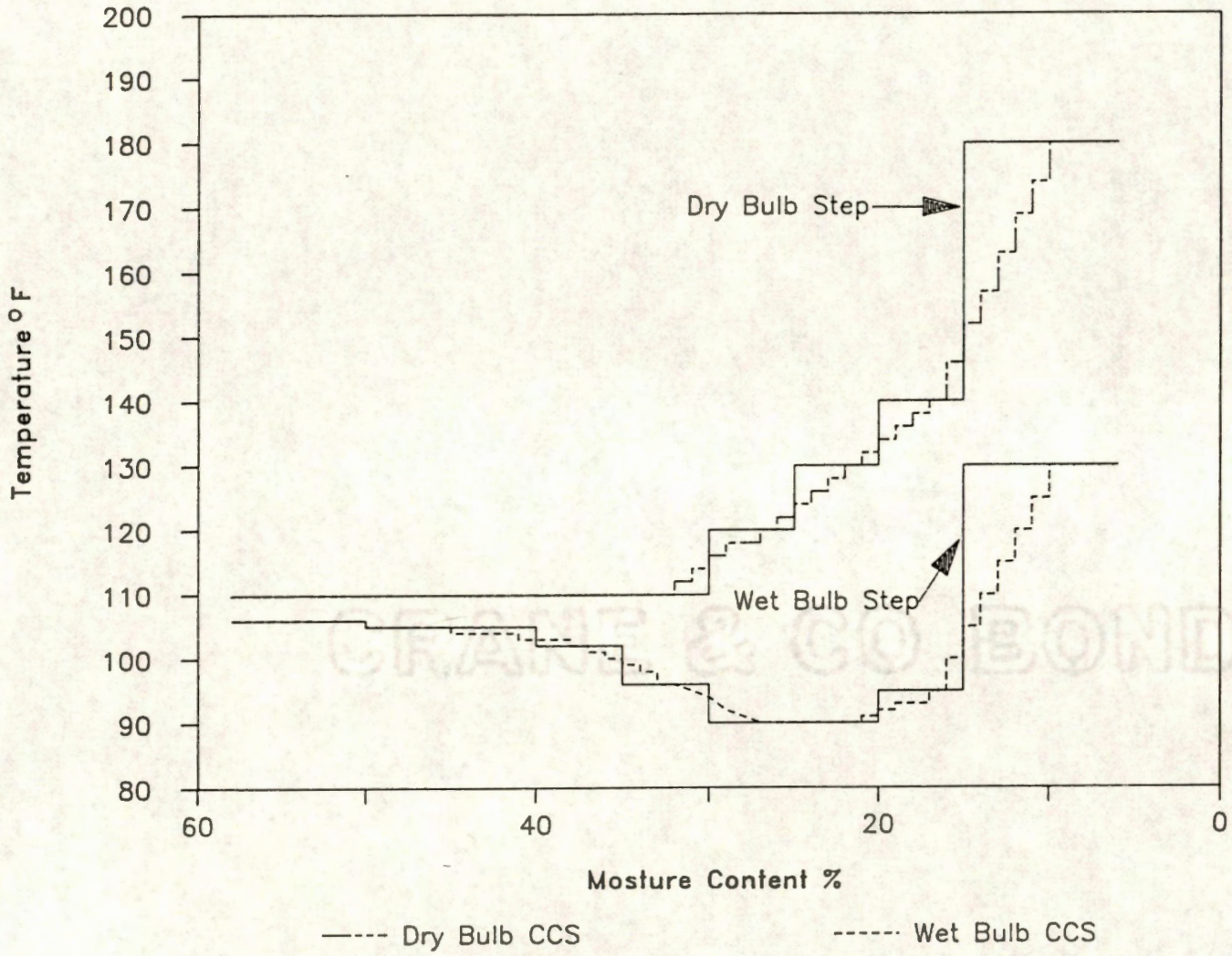


Figure III-2. Step and a Midpoint CCS Mini Step Compared

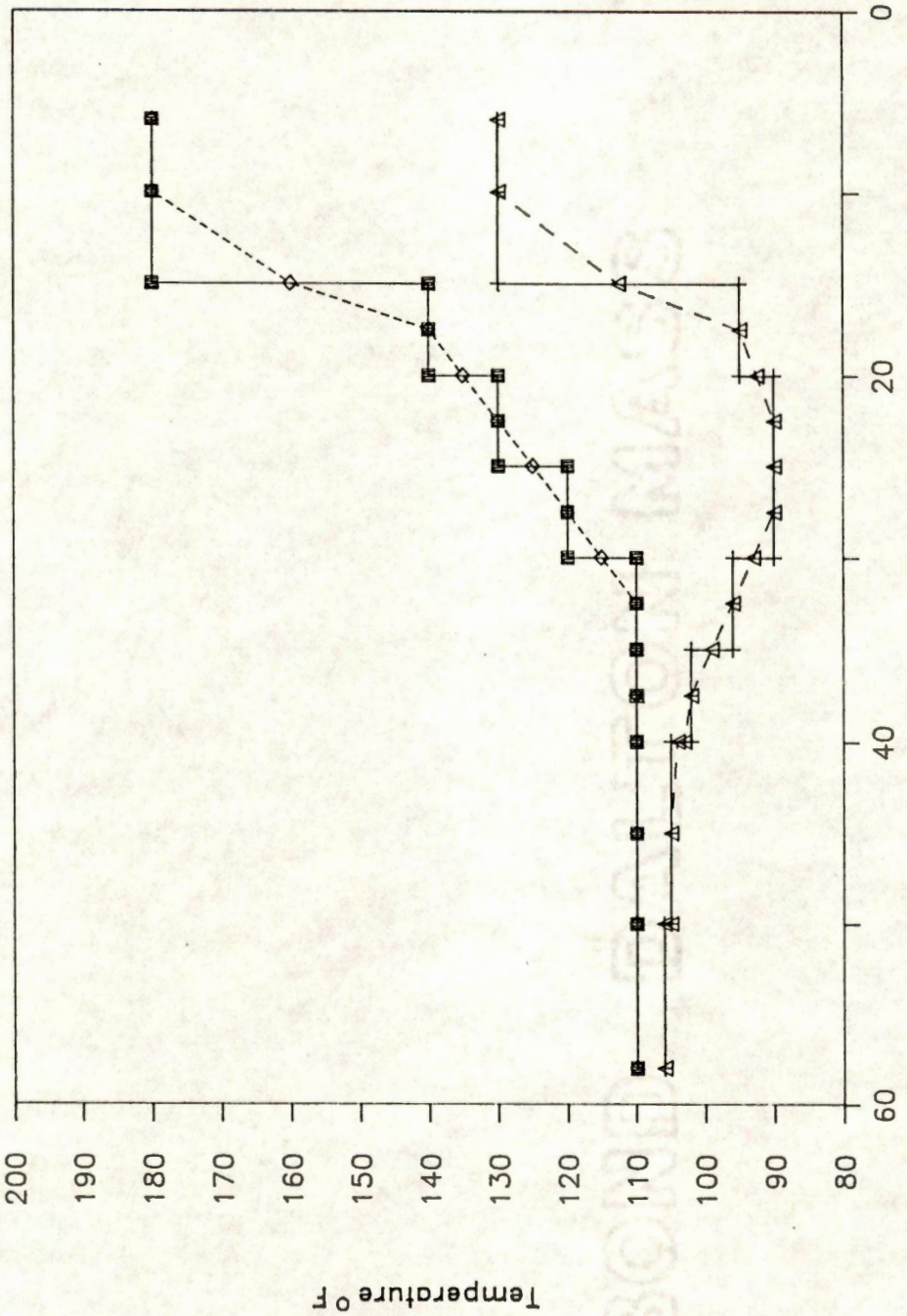


Figure III-3. Hardwood Step Drying Schedule T4D2 and Midpoint Example

(2) For both charges, initial moisture contents were calculated manually. Daily moisture contents were calculated manually by the ovendry weight method and by the computer which continuously monitored the in-kiln moisture meter and load cells. Kiln temperature conditions were recorded continuously for the wet and dry bulb set points, and the actual dry bulb and wet bulb temperatures. Energy use was monitored in the form of steam temperature, pressure, volume, and flow. Also recorded were frequency of operation for the spray, heat and vent systems. Each record was dated with the elapsed time.

(3) After the charges dried to 6 percent moisture content, the data was analyzed by computer. Drying schedules and the various conditions were graphically reconstructed. Comparison of the two schedules was made with summary tables and graphs.

Step Schedule Trials

Incidents

The step schedule test was started on January 27, 1987. About 800 board feet, of common and better, rough green, 8 foot long, one inch red oak lumber was transported from a flooring plant in Johnson City, Tennessee to the Mengel Forest Products Laboratory at the University of Tennessee, Knoxville. The lumber was covered en route to protect it from wind damage, and promptly stacked on 3/4 inch thick stickers on arrival. Moisture samples were immediately prepared and a record sheet begun.

A start up problem with load cell calibration was determined to be caused by overloaded kiln carts. A layer of lumber was removed to bring the weight within instrument limits (below 3845 pounds).

The kiln was started at 4 P.M. on January 30. There were two recorded power outages during drying necessitating restarts. During a normal step change the wet bulb set point for step six was mistakenly set as 80 instead of 90 degrees. During the final step a faulty relay caused high dry bulb readings, it was replaced. After a run of 822 hours the lumber reached 7.0 percent moisture content. The kiln was turned off at 4 P.M. on March 8, after conditioning and equalizing.

The overall appearance of the lumber on final examination was excellent. There was a small amount of stain, moderate to light end checking (4 inches or less), and light, shallow, and scattered surface checks.

Continuously Changing Schedule Trials

Creating a Mini Step Schedule

A midpoint schedule was chosen as the model for the trial CCS. A maximum schedule may have the potential of harming red oak. A minimum schedule may take too long to be effective in comparison with other schedules. The midpoint schedules have been found to be moderate by other researchers (Alexandrou, 1980), and was the choice for a first CCS attempt on eastern hardwoods.

The design principles used to prepare the schedule can be seen in Figure III-3. Step schedule T4D2 is converted to a mini-step CCS by

finding the convenient points along the midpoint lines which differ from the previous point more by than one degree Fahrenheit and 1 percent moisture content. This is done for both dry and wet bulb. The result (Figure III-2) is a smoothing of the old steps into a mini step schedule which is recognized within the limits of the computer controller as a continuously changing schedule.

Computer Programming and Modification

The computer program which controls the dry kiln (Kiln Comp) can store, recall, and use any step schedule of ten or fewer steps. A routine in the controlling program was modified to use the new 32 step CCS. A few other variables in the program were given new values to accommodate the greater number of steps. Except for these necessary changes, the original program functioned without incident.

Incidences

The lumber for the continuously changing schedule run was transported on March 17, 1987. Samples were cut and processed the next day. A delay in completing the computer programming start-up until 9:30 AM March 24.

After three weeks, the drying rate slowed to less than 1 percent moisture content loss per day. The sample moisture contents and the load cell moisture contents were diverging. It was judged that the five day wait between cutting and processing the moisture samples and starting of the kiln caused a moisture content discrepancy. The lumber had dried by this time to an average 42.5 percent moisture content. The

ovendry weight of the load cell was adjusted to match the sample weight. After adjustment the computer controller immediately engaged mini step 3, bypassing step 2. There were no other discrepancies.

After a run of 1133 hours the lumber reached 6.1 percent moisture content. The kiln was turned off after conditioning and equalizing at 8 A.M. on May 11.

Examination of the lumber was done after drying. There was essentially no difference in apparent quality from the first run. No drying defects were severe enough to devalue the lumber.

Results of the Trials

The computer data from each run was greater than 500 thousand bytes. Therefore, a basic computer program "Data Conversion" (Appendix) was written to eliminate unwanted extra data, exclude redundant records with temperature changes less than one degree, and place the remainder in a transferable format. Data storage for each run was reduced to less than 300 thousand bytes which was placed on one diskette. The "Symphony®" program package was used to organize the data, calculate drying rates, and prepare graphs.

Attempts to record usable energy use data did not succeed. Large portions of the data for the CCS run were unavoidably lost in transferal and could not be recovered.

Step Schedule Results

The first run had an overall drying rate of 2 percent moisture content loss per day (Table III-4). The lumber took 34 days to dry from an initial moisture content of 74.2 percent to 7 percent.

It was noticed that the sample and the load cell moisture contents were in close agreement (with the latter about 2 percent less) through the drying cycle (Figure III-4). After the charge reached about 10 percent moisture content the load cell moisture content reading stalled and went no lower. The sample moisture content continued down to 7 percent.

As seen in Figure III-5 the recorded dry bulb oscillated about four or five degrees around the set point. The fan reversals at six hour intervals are distinguishable. The peaks and valleys are very sharp because of the small volume of the kiln. The faulty dry bulb probe is obvious in the last step.

CCS Results

The CCS charge took 47 days to dry from 79.7 to 6.1 percent moisture content. Like the step schedule run the lumber was green; the drying slow-down lengthened the drying time.

The calibration error also resulted in a slower overall drying rate of 1.6 percent moisture content per day (Table III-5). The correction is seen (Figure III-6) as a pronounced hump on the moisture content line. After the equipment was recalibrated the controller responded as designed.

Table III-4. Results of Trial Using Step Schedule FPL T4D2

Step Number	Settings Dry Bulb °F	Settings Wet Bulb °F	Run Time Hours	Sample Moisture Content %	Load Cell Moisture Content %	Moisture Content % Loss/Day
Start	--	--	0.0	74.2	74.9	--
1	110	106	383.2	50.4	47.5	1.72
2	110	105	154.6	39.4	37.5	1.58
3	110	102	47.2	34.6	32.3	2.56
4	110	96	45.8	29.4	27.0	2.76
5	120	90	22.7	24.5	22.7	3.94
6	130	80	48.9	17.7	16.7	2.98
7	140	90	44.4	13.9	14.1	1.66
8	180	130	71.6	7.0	9.9	1.25
Entire Run			822.0			1.96

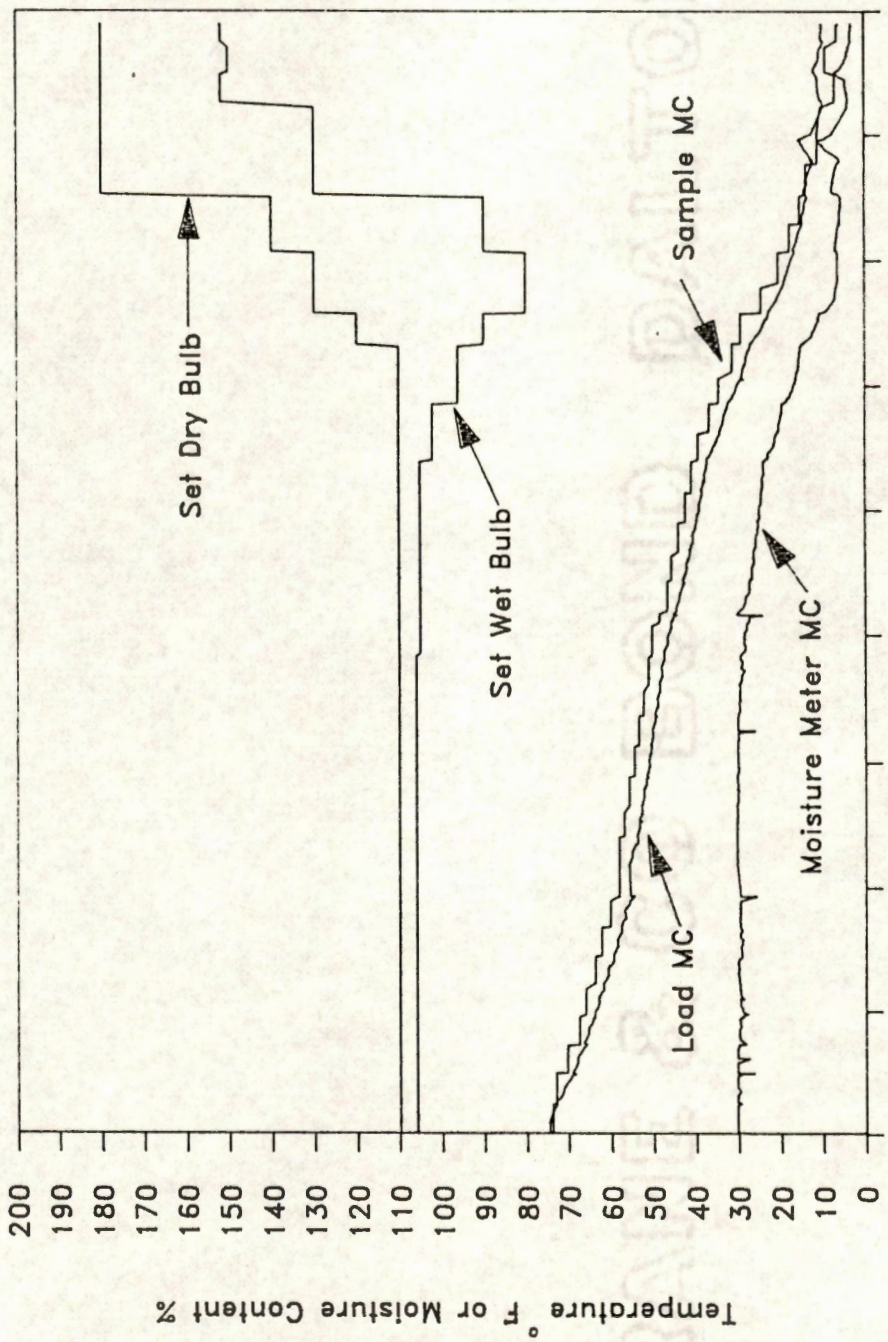


Figure III-4. Step Schedule Trial Results

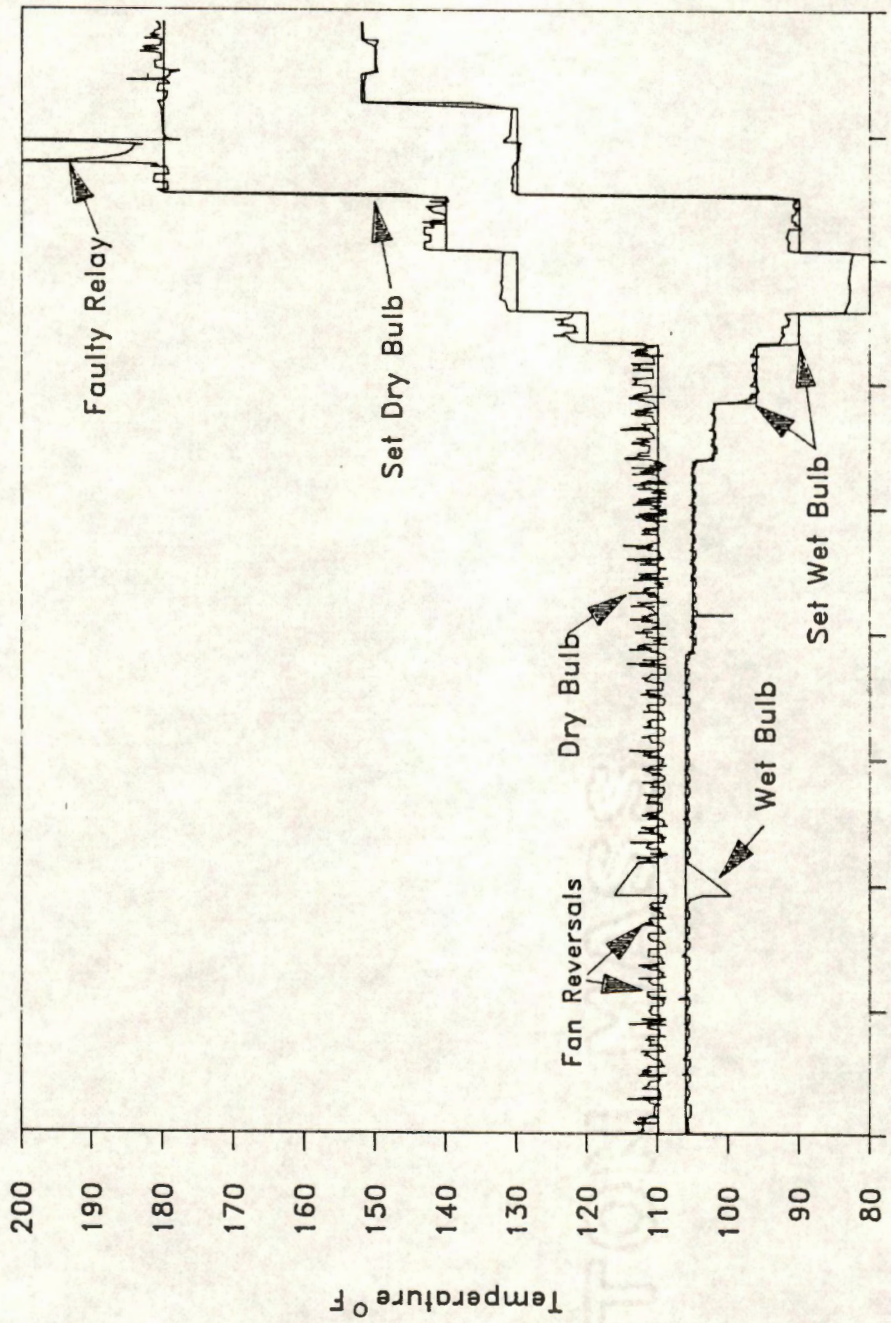


Figure III-5. Step Schedule Set and Actual Temperatures

Table III-5. Results of Trial with CCS Mini Step

Step Number	Settings Dry Bulb °F	Settings Wet Bulb °F	Run Time Hours	Sample Moisture Content %	Load Cell Moisture Content %	Moisture Content % Loss/Day
Start	--	--	0.0	79.7	79.0	--
1	110	106	700.6	43.6	42.8	1.16
3	110	104	22.6	43.1	41.0	1.91
4	110	103	37.6	38.9	37.9	1.90
5	110	102	9.8	38.9	36.9	2.50
6	110	101	10.6	36.6	35.9	2.31
7	110	100	9.5	36.6	35.0	2.30
8	110	99	5.1	36.6	34.0	4.94
9	110	98	12.7	36.6	33.0	1.97
10	110	96	7.5	36.6	32.0	3.20
11	112	96	4.4	36.6	31.2	4.35
12	114	95	11.6	31.3	29.9	2.63
13	116	94	7.2	31.3	29.0	2.07
14	118	92	17.9	27.5	27.0	2.81
15	120	90	9.1	27.5	26.0	3.16
16	122	90	9.6	25.4	25.0	2.58
17	124	90	11.4	25.4	24.0	2.08
18	126	90	5.4	24.0	23.0	4.22
19	128	90	11.9	22.8	22.0	1.94
20	130	90	11.4	22.8	20.9	2.42

Table III-5. (Cont.)

Step Number	Settings Dry Bulb °F	Settings Wet Bulb °F	Run Time Hours	Sample Moisture Content %	Load Cell Moisture Content %	Moisture Content Loss/Day
21	132	91	13.9	20.4	19.9	1.65
22	134	92	3.9	20.4	19.0	1.17
23	136	93	24.7	18.1	18.0	1.78
24	138	93	6.8	18.1	17.0	3.32
25	140	95	22.4	16.2	16.0	1.12
26	146	100	20.1	14.3	15.0	1.19
27	152	105	16.3	12.3	14.0	1.49
28	157	110	14.4	10.5	13.0	1.65
29	163	115	15.2	10.5	12.0	1.01
30	169	120	36.2	8.8	11.0	1.09
31	174	125	33.2	7.1	10.0	1.00
32	180	130	25.3	6.1	9.1	0.86
Entire Run			1133.2			1.56

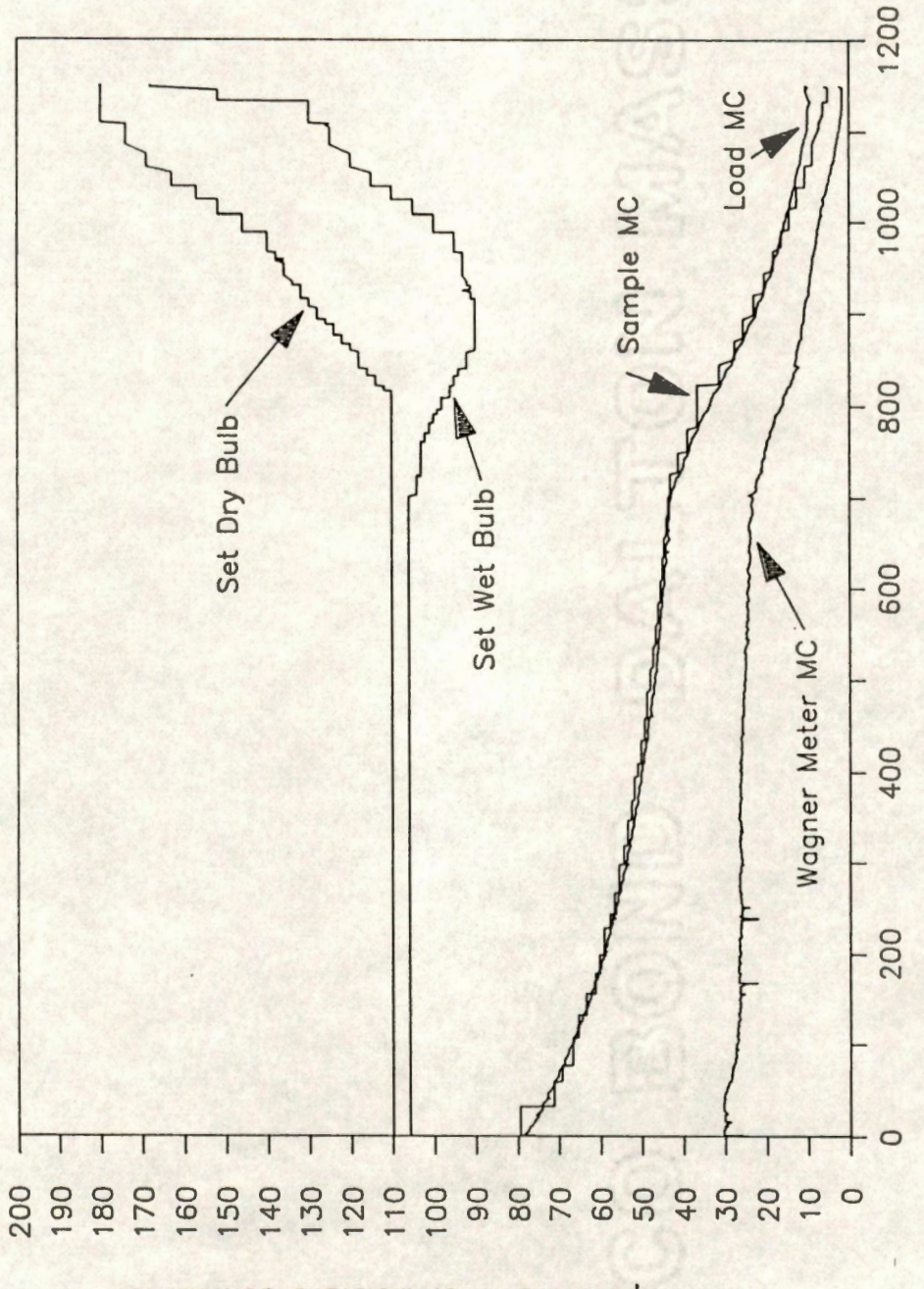


Figure III-6. CCS Trial Results

As in the step schedule run, the sample and the load cell moisture contents reflect each other closely (Figure III-6). After the run reached about 10 percent moisture content the load cell moisture content stalled and went no lower. The sample moisture content continued down to 6.1 percent.

As seen in Figure III-7, the recorded dry bulb oscillated about four or five degrees around the setting. The recorded wet bulb fluctuated less than two degrees. After schedule changes began, both temperatures remained one or two degrees above set point. The fan reversals at six hour intervals are distinguishable.

The computer and its programming performed well throughout the entire run. There was no time loss because of computer outage or programming errors. The programming had one minor problem. The data is averaged over about a 14 minute period. From these averages the kiln temperatures are set. Several times when the moisture content was near a schedule change the set points jumped back and forth, in 14 minute periods, as the weight fluctuated. There was no harm or inconvenience apparent because of the small temperature changes between steps.

The Schedule Trails Compared

Results of the two schedules (after the CCS recalibration at 42.5 percent moisture content) are visually compared in Figure III-8. Step schedule and CCS results are over-laid (from 42.5 percent moisture content to end-of-run), and show very similar drying curves. The CCS was noticeably slower by about 50 hours. The CCS temperatures (in

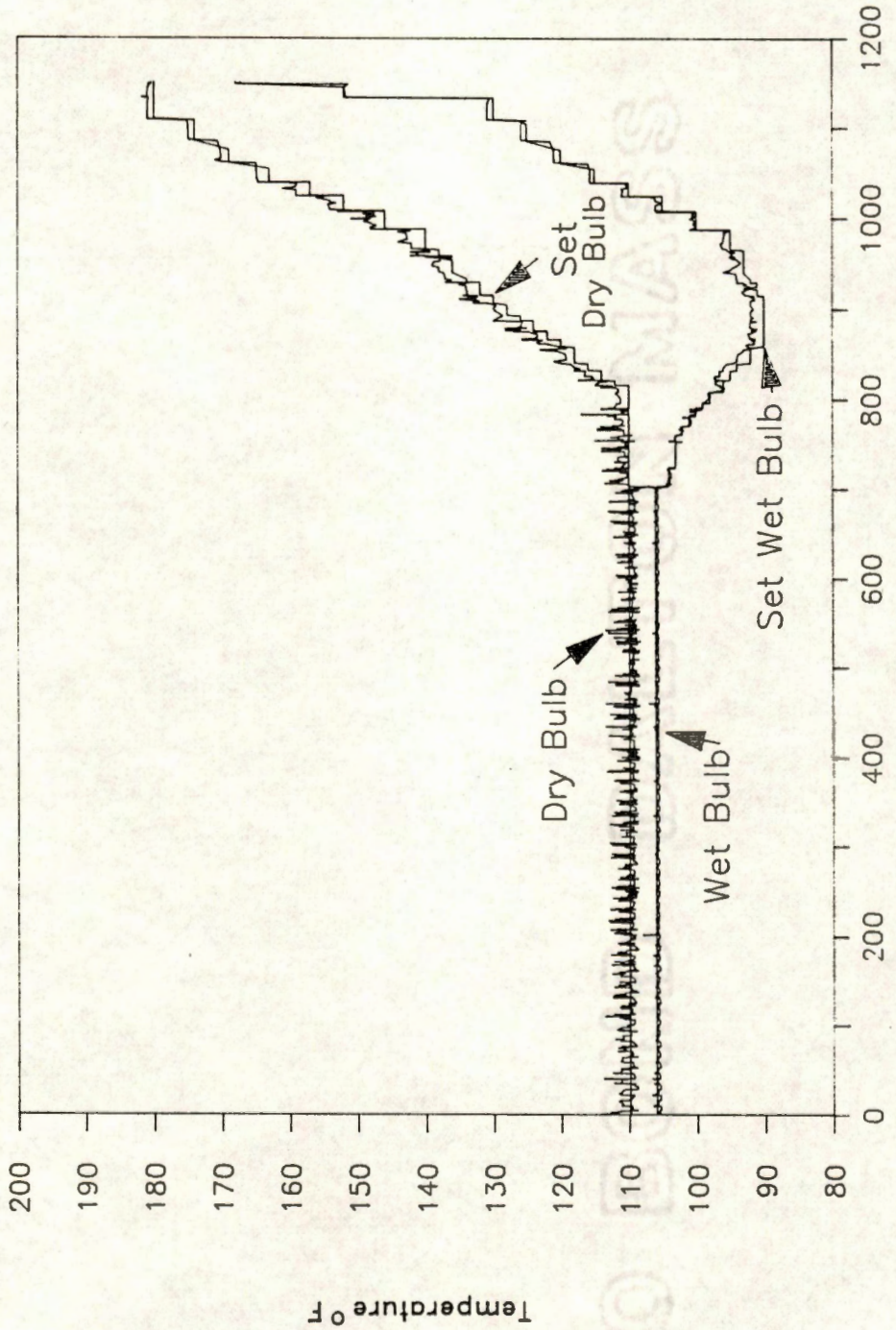


Figure III-7. CCS Set and Actual Temperatures

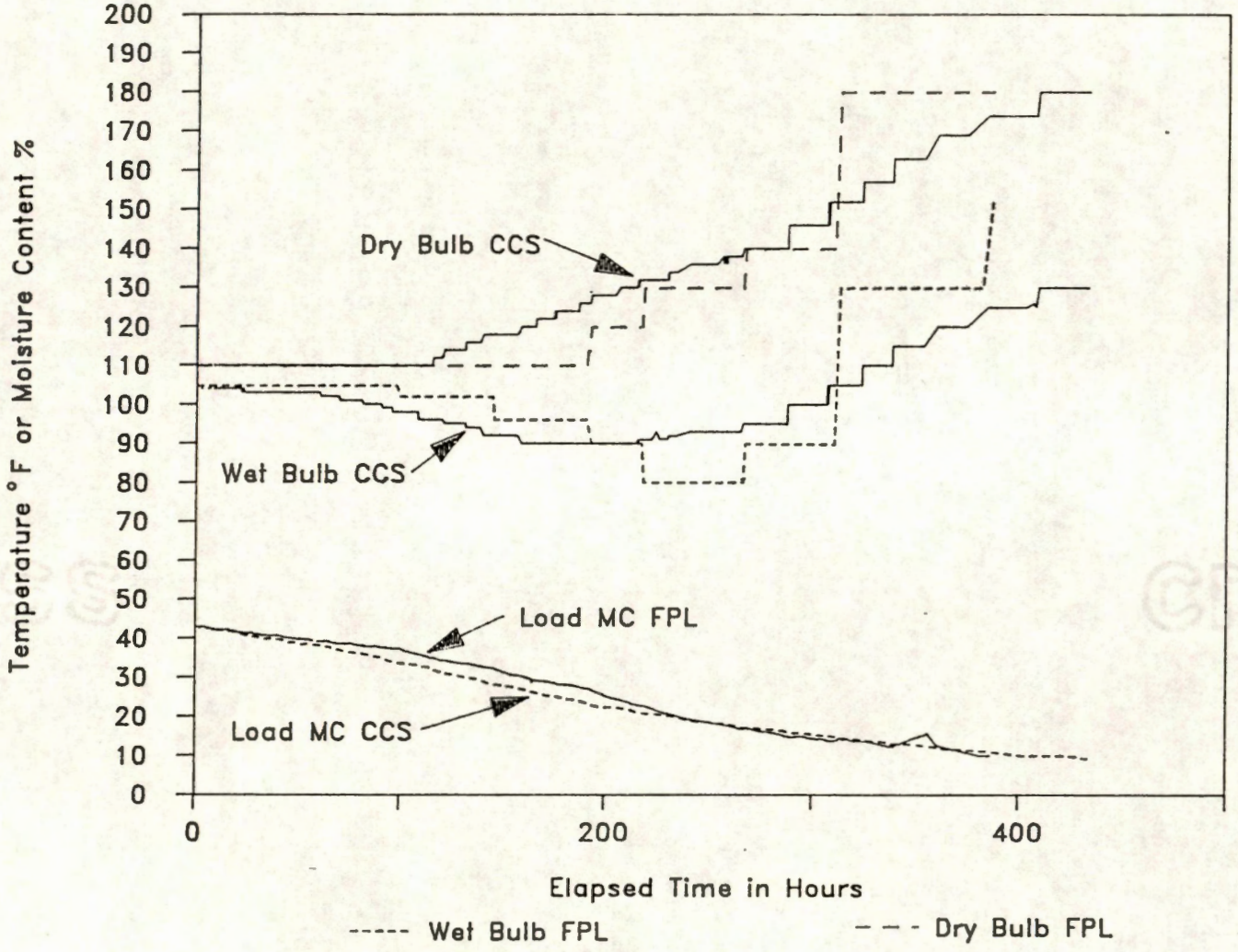


Figure III-8. Schedule Comparison from 42.5 Percent MC for Load Cell MC

comparison to the step schedule) followed the design model as a midpoint schedule.

When comparing similar segments of the moisture content drying curve for both runs (Figure III-9), where the limits are the sample moisture content nearest 42.5 percent and the 7 percent readings, the CCS took 40 hours more. Energy use calculations made by the method described in Chapter II, for the same segment, showed that the step schedule used 2.10 million Btus per MBF and the CCS 1.99 million Btus per MBF.

The mini step CCS designed for 4/4 red oak is slower than the T4D2 schedule and would be conservative for commercial use. It also uses 5.1 percent less energy. This was not unexpected and agrees with previous attempts with midpoint schedules by Alexandrou (1980). Future design work should consider faster, more severe maximum point schedules which may decrease drying time for 4/4 red oak.

Most importantly, the test shows that a continuously changing schedule in mini step form can be made using existing information. The mini step format is compatible with micro computer based control systems. Future work with continuously changing dry kiln schedules for hardwoods is possible with this control equipment.

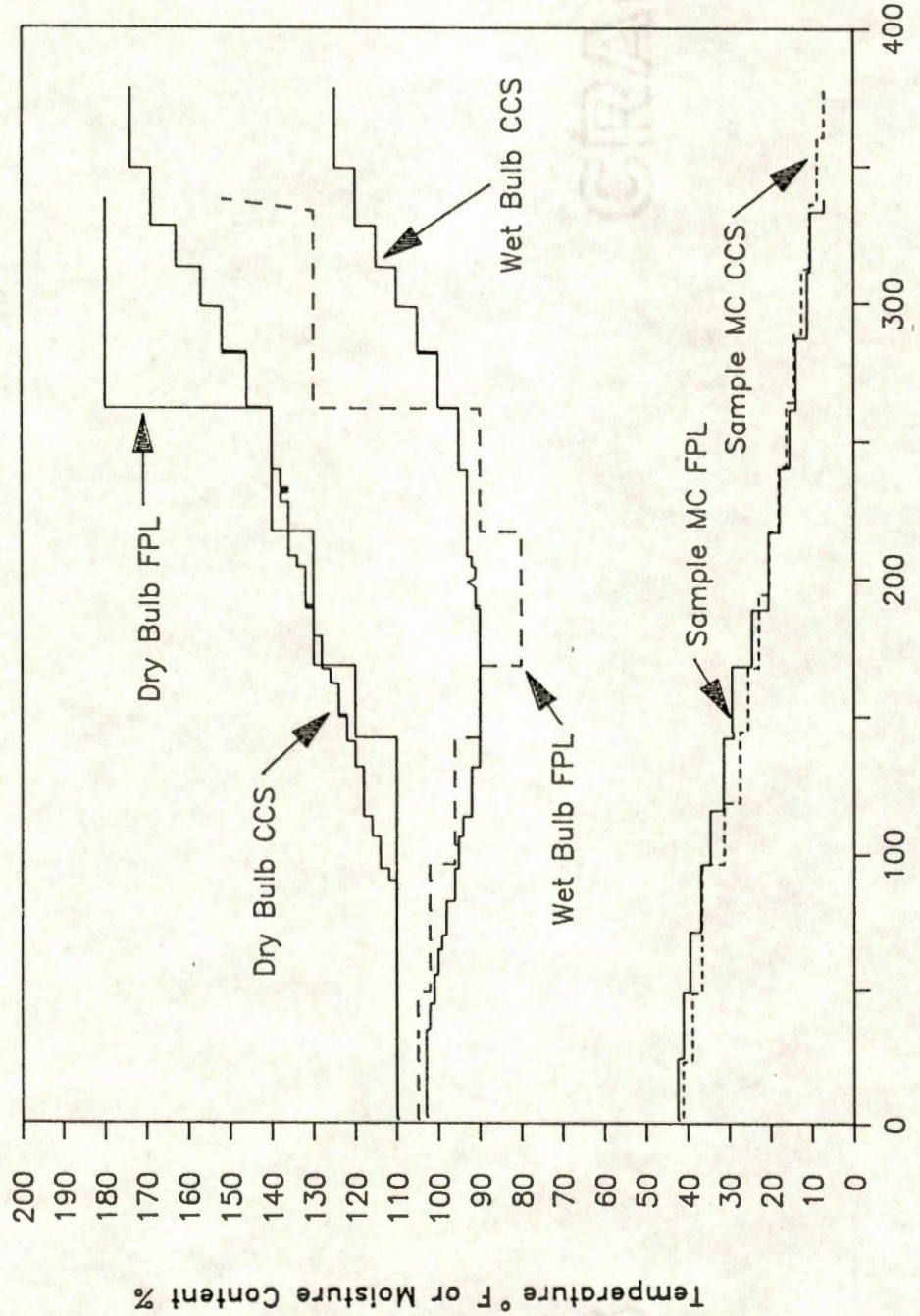


Figure III-9. Schedule Comparison from 42.5 Percent MC for Sample MC

CHAPTER IV

CONTINUOUS DRYING EQUATIONS

Equation Development

The most desirable form of continuously changing hardwood drying schedules are mathematical equations. These equations would use wood moisture content as the independent variable in a mode finding dependent variables such as dry bulb or wet bulb. This would completely free the drying lumber from schedule steps allowing drying on a continuum basis. In addition, a continuously changing equation would have flexible programming and schedule assembly. It would allow interaction between the control of drying conditions such as fan speed, or other future developments. Finally, CCS equations would compliment the higher accuracy of the new computer controllers.

The Method of Equation Determination

It was reasoned that two equations would be needed; one for dry bulb, and another for wet bulb. Moisture content was selected as the best choice for the independent variable, since it is commonly used in step schedules. Further, to limit potential degrade, the FPL hardwood schedules were used as guides.

A nearly linear relationship was noticed between the maximum point dry bulb temperatures of an FPL step schedule and moisture content (McMillen and Wengert, 1978) when graphed. A least squares regression method suggested a satisfactory fit using moisture content to predict

dry bulb temperature. The same procedure on other dry bulb schedules had similar results, although some were not linear, and needed more complex equation models.

Four regression formula models were tested for eight dry bulb schedules. Regression analysis found equations for:

$$\text{Linear:} \quad DB = a + b \times MC$$

$$\text{Logarithm:} \quad DB = a + b \times \ln MC$$

$$\text{Power:} \quad DB = a \times MC^{b}$$

$$\text{Base e:} \quad DB = a \times e^{bMC}$$

Where:

Dry bulb temperature = DB

Moisture Content = MC

Slope of the line = b

and Y intercept = a

The equation of the model with the best R square value was selected as the closest fit for each schedule. All equations selected for FPL schedules which predict dry bulb temperature using moisture content (Table IV-1) had R squares above 0.97. Figure IV-1 compares a step schedule and the derived CCS.

Developing formulas for predicting the wet bulb temperature was more difficult. The curve resulting from plotting most hardwood wet bulb temperatures against moisture content is spoon shaped and difficult to describe mathematically (Figure IV-2). The inability to fit wet bulb

Table IV-1. Equations for Predicting Dry Bulb Temperatures

Dry Bulb Schedule FPL	Formula Number	Formula	R^2	Limits for Temperature Higher °F	Lower °F
T-2	(D-1a)	$DB = 185.55 - 2.52MC$	0.98	160	100
T-2	(D-1b)	$DB = 440.42MC^{-0.41}$	0.98	160	100
T-3	(D-2a)	$DB = 510.38MC^{-0.43}$	0.99	160	110
T-3	(D-2b)	$DB = 205.66e^{-0.02MC}$	0.99	160	110
T-4	(D-3)	$DB = 772.28MC^{-0.55}$	0.97	180	110
T-5	(D-4)	$DB = 190.00 - 2.00MC$	1.00	160	120
T-6	(D-5)	$DB = 610.86MC^{-0.46}$	0.98	180	120
T-8	(D-6)	$DB = 212.00 - 2.40MC$	0.97	180	130
T-10	(D-7)	$DB = 210.00 - 2.00MC$	1.00	180	140
T-11	(D-8)	$DB = 200.00 - 1.40MC$	0.98	180	150

Dry Bulb in Degrees Fahrenheit = DB

Moisture Content in Percent = MC

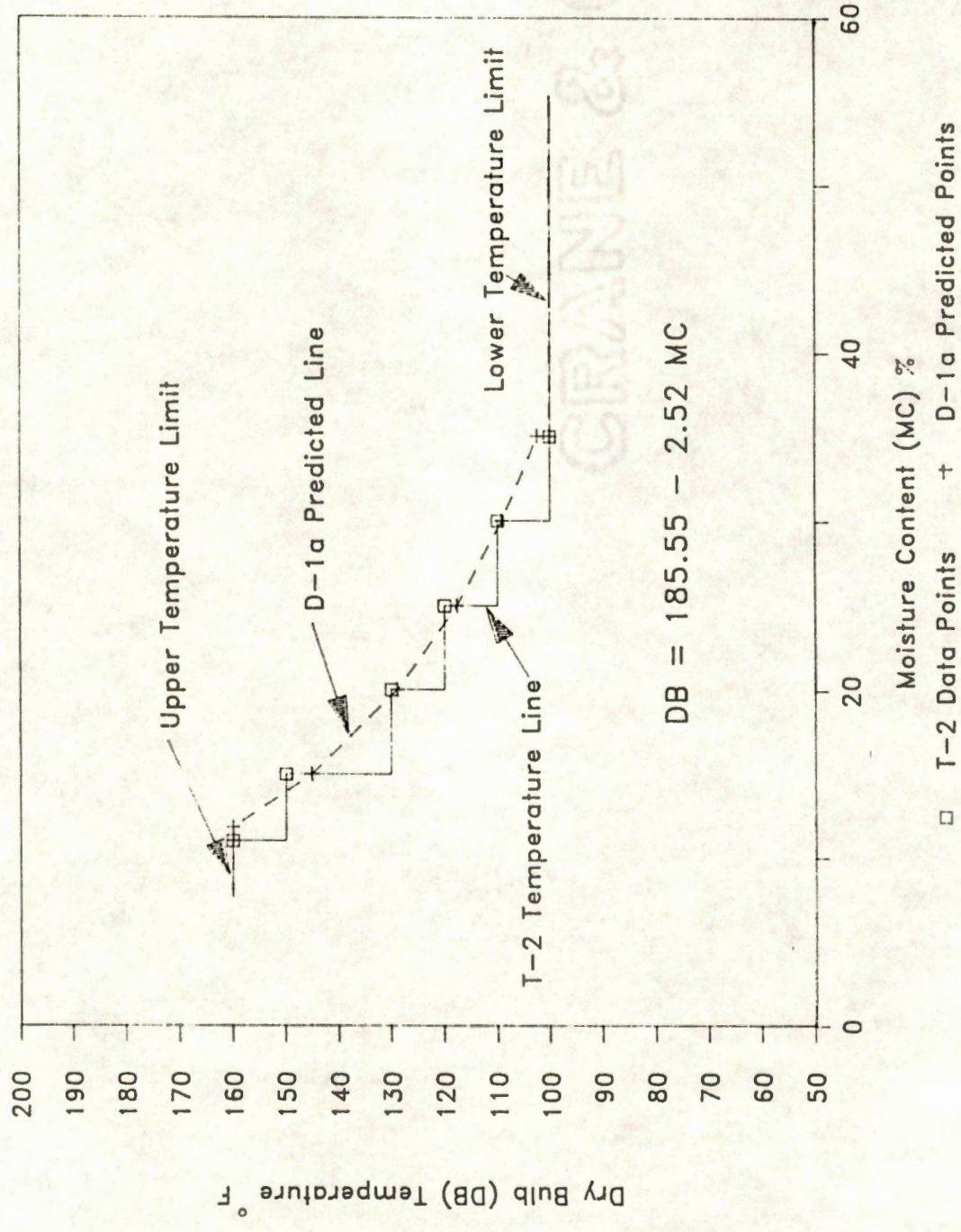


Figure IV-1. FPL T2 Dry Bulb and Prediction Line

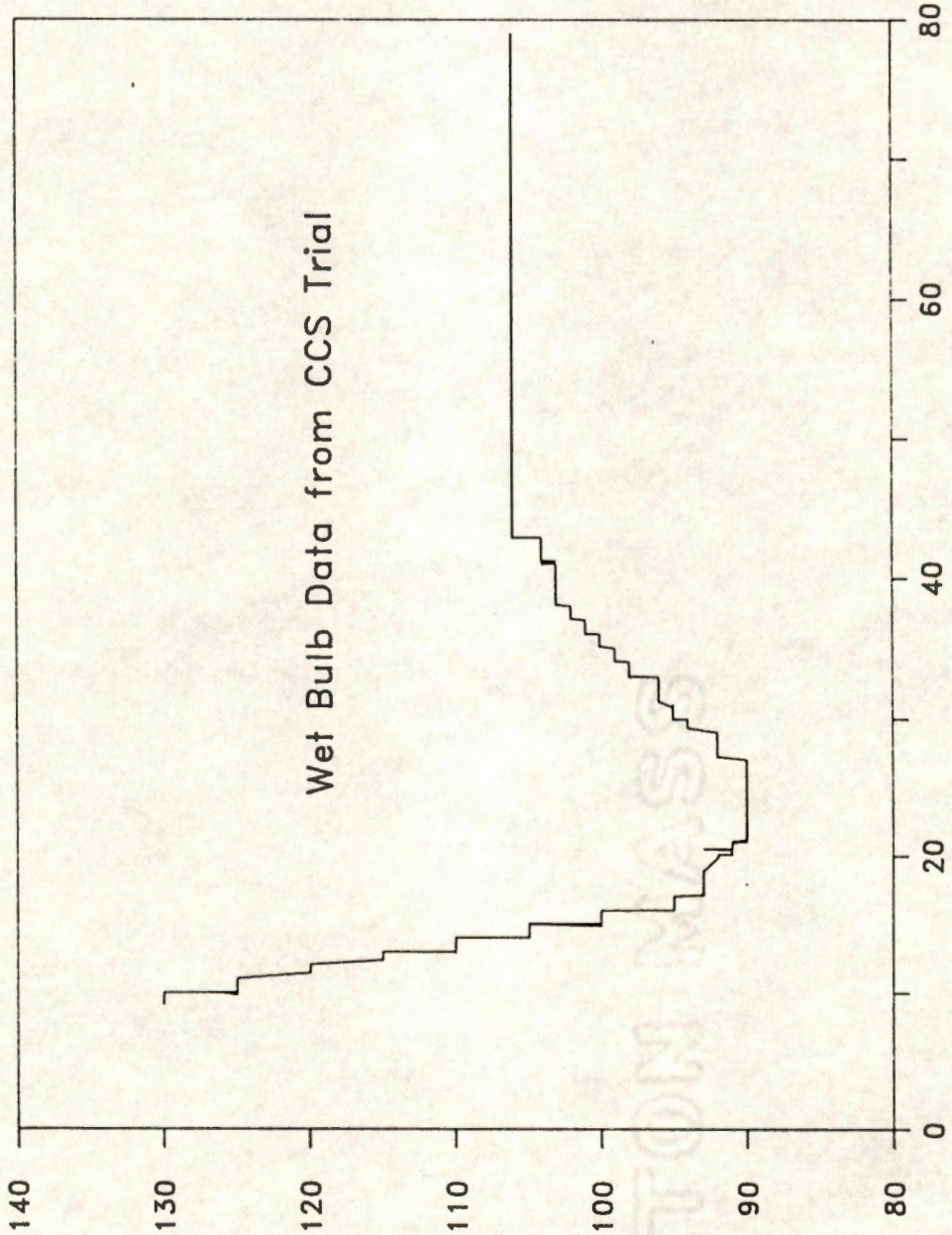


Figure IV-2. A Wet Bulb Temperature/Moisture Content Line

equations easily and accurately has been a recurring problem in CCS equation development.

It was noticed that the wet bulb depressions had a conventional shaped curve when plotted against moisture content. Using the same regression models previously used for the dry bulb schedules, but with wet bulb depression as the dependent variable, a series of equations which predict wet bulb depression based on moisture content (Table IV-2) were found. It is possible to derive the wet bulb temperature by subtracting the computed WBD from the computed dry bulb at the same moisture content.

Finally, it must be stated that these equations are not presented as the final example or the absolute best possible curve fits. The data used was derived from tables of values which are known to already have relationships, and there were a limited number of data points. Therefore further statistical tests were excluded. There may be more accurate, complex mathematical descriptions of these temperature vs. moisture content curves and more systematic methods of finding them. However the equations found and described usefully predict temperatures with adequate accuracy for this study and the resolution of existing kiln equipment.

Examples

Examples of the equation determining method are shown on Tables IV-1 (dry bulbs) and IV-2 (wet bulb depressions). These are based on some of the most commonly used FPL step schedules. Also, included with the formulas are high and low temperature or moisture content

Table IV-2. Equations for Predicting Wet Bulb Depression Temperatures

Wet Bulb Schedule Content FPL	Formula Number	Formula	R^2	Limits for Moisture Higher °F	Lower °F
C-1	(W-1)	$WBD = 247.28e^{-0.10MC}$	0.98	15	45
C-1°	(W-2)	$WBD = 186.27e^{-0.09MC}$	0.96	11	45
C-2°	(W-3)	$WBD = 254.47e^{-0.09MC}$	0.97	15	45
C-3	(W-4)	$WBD = 197.36e^{-0.08MC}$	0.99	15	45
C-4	(W-5)	$WBD = 173.18e^{-0.07MC}$	0.97	15	45
D-1	(W-6)	$WBD = 206.15e^{-0.08MC}$	0.95	15	55
D-2	(W-7)	$WBD = 195.74e^{-0.07MC}$	0.96	15	53
D-3	(W-8)	$WBD = 163.08e^{-0.06MC}$	0.96	15	55
D-4	(W-9)	$WBD = 67.32 - 1.15MC$	0.97	15	55

Wet Bulb Depression in Degrees Fahrenheit = WBD

Moisture Content in Percent = MC

°Modified FPL schedules

limits, for the respective FPL step schedules, between which the dry kilns function.

A dry bulb equation and a wet bulb depression equation were derived from the familiar FPL schedule for 4/4 red oak T4D2 (Figure IV-3). The step schedule reference points and predicted CCS lines are shown. The dry bulb equation line in the figure fits the description of a maximum point CCS.

A concern in developing CCS equations is that resulting data will not be accurate enough to describe some of the critical wet bulb depressions. For example, the green stages of drying refractive hardwoods often requires a WBD of three or four degrees. However, it was found that the equations could describe the WBD within needed limits. In fact, the CCS equations are hypothetically more accurate than other controlling methods and may be able to control a smaller WBD.

Equation Use

A Flow Chart for Computer Programming

Programming a computer controlled kiln similar to the one at the University of Tennessee to use CCS equations should not prove difficult. A similar modification has already been accomplished for CCS mini steps. The computer programming flow chart in Figure IV-4 is intended for future use with KILN COMP or a similar kiln controlling program.

It is recognized that constantly changing kiln temperatures as provided by the equations could cause unnecessary wear on kiln equipment such as, pipes, values, and vents. It is suggested that

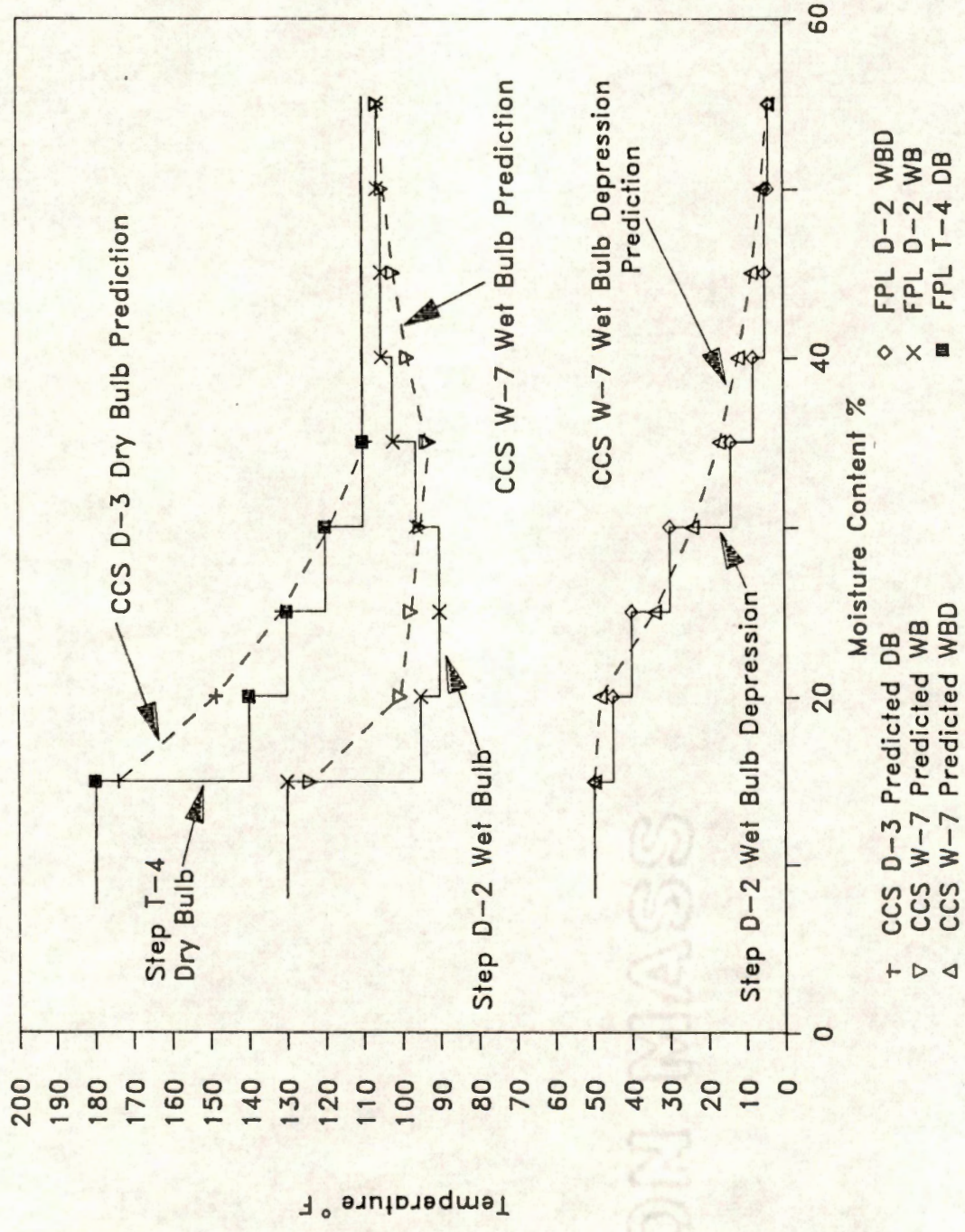


Figure IV-3. Equation Lines for T4D2

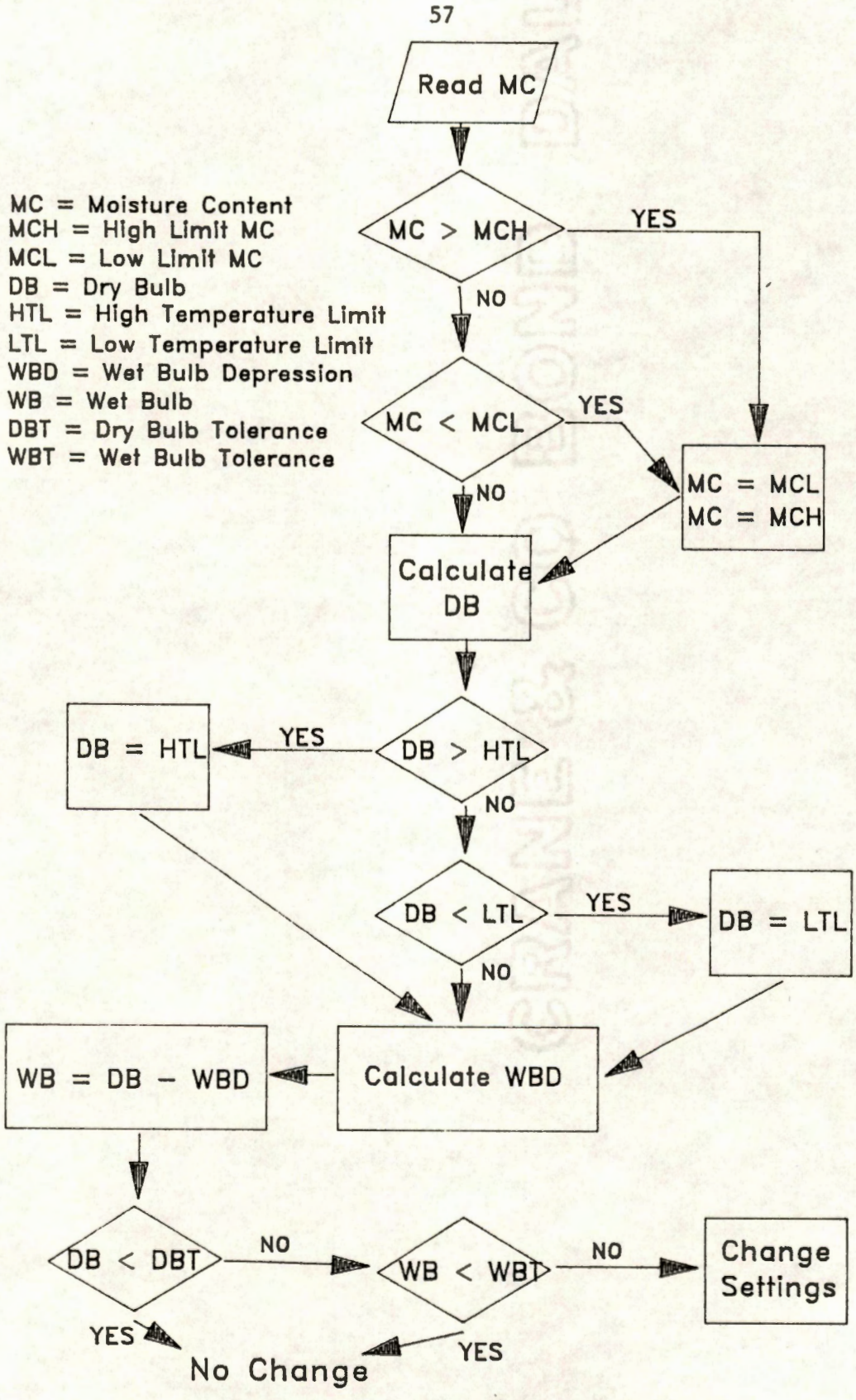


Figure IV-4. Flow Chart of Suggested CCS Equation Computer Use

temperature ranges (tolerances) be considered which will not conflict with reasonable operation or efficiency similar to the dwell on most conventional controllers. These tolerances should be chosen by the user to compliment their equipment.

In the flow chart (Figure IV-4) the computer begins a cycle by reading and/or calculating the moisture content (MC) from any established method. The first operation defines the upper and lower MC limits in which the schedule will function. If the MC is greater than the high limit moisture content (MCH) it will use the MCH in place of the MC in the dry bulb (DB) and wet bulb depression (WBD) calculations. Similarly, if the MC is less than the low limit moisture content (MCL) it will equate MC to MCL. The DB is then calculated using one of the CCS DB equations.

The next operation compare the calculated DB with the suggested DB temperature limits and ensures they remain within them. If the DB is greater than the high temperature limit (HTL) it is replaced by the HTL. And if the DB is less than the low temperature limit (LTL) it is replaced by the LTL. Then the WBD is calculated using one of the CCS WBD equations. The wet bulb (WB) is also calculated.

In the last operation of the flow chart the current calculated DB and WB are compared to the calculations of the previous cycle. If the difference between the previous WB or DB temperature and those current is less than their respective tolerances, expressed in degrees Fahrenheit, the controller will cycle again without changing temperature

settings. If both differences are greater than the allowed tolerance the settings will change to the current WB and DB.

Potential Uses

Many new and existing commercial computer controllers may have the capability to use mathematically based CCS. As demonstrated by this study, changing to a CCS control system is primarily a programming function.

Schedule modifications are possible. The separation of dry bulb and wet bulb depression formulae allow them to be matched to any corresponding dry bulb or wet bulb formula. This makes it possible to safely investigate new schedules options. Also, schedule curve shifts along the moisture content line should increase or decrease drying times and quality. This could all be done on the computer within safety limits and without cumbersome books, paper, graphs, and procedures.

CHAPTER V

CONCLUSIONS

Two methods for the development of CCS for eastern hardwoods were developed. The first (mini step CCS) converted a 4/4 Red Oak step schedule into small steps which dry kiln controllers identified as a CCS. The second method (equation CCS) used regression equations to predict dry bulb temperatures and wet bulb depressions from moisture content.

The economic potential of CCS for hardwoods was estimated. An energy savings of 6.5 percent was calculated for a CCS. CCS has an estimated 1.01 dollar per MBF energy savings when drying 4/4 green red oak. A hypothetical 180 MBF commercial lumber drying operation scenario using CCS saves 2.39 dollars per year in energy and investment costs. Pay back on the cost of the computer equipment would be approximately 4 years.

The use of CCS with a computerized controller for eastern hardwoods was demonstrated. A mini step CCS for 4/4 red oak was adapted to University of Tennessee's computerized dry kiln controller. The adaptation was a modification of the existing controlling computer program. One drying run was made using manual control. A CCS drying run was demonstrated with no significant operating problems or drying defects. Results showed that the midpoint CCS schedule took 11 percent longer to dry, but used 5.1 percent less energy than a similar step schedule over the same moisture content percent range.

The trials showed that the accuracy of computer equipment must be matched by a corresponding accuracy of techniques and procedures. Automatically controlled kilns can overcome some human errors, but new equipment and procedures create the potential for new forms of errors. The mini step CCS designed for 4/4 red oak was slower than T4D2 schedule and may be too conservative for commercial use. The trials also showed that a continuously changing schedule in mini step form, can be developed using existing information. Future work with continuously changing dry kiln schedules for hardwoods should test the effectiveness of equation generated kiln settings on drying efficiency, quality and cost.

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BIBLIOGRAPHY

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Alexandrou, C. C. The Development of Continuous-Change-Schedules for the Kiln Drying of Lumber. Master of Science Thesis. University of California, Berkely, 1980.

Bois, Paul J. The Four Stages of Drying in Thick Oak. Forest Products Research Society, News-Digest, J-1.3. 4 pages, December, 1977.

Bramhall, G. Mathematical Model for Lumber Drying, I. Principals Involved and II. The Model. Wood Science, Vol. 12, No.1., Pages 14-31, July, 1978.

Comstock, G. L. Energy Requirements for Drying of Wood Products. Wood Residues as an Energy Source. Forest Products Research Society, Madison, Wisconsin, 1975.

Corder, S., E. Potential for Energy Recovery fron Lumber Dry Kilns. Forest Products Journal, Vol. 30, No. 8. Pages 30-35, August, 1980.

Dedrick, D., S. Accelerated Drying by Control of Air to Wood Temperature Differential. Forest Products Research Society, News-Digest, F-6.13. 3 pages, October, 1970.

DeGarmo, E. P., W. G. Sullivan and J. R. Canada. Engineering Economy. Seventh Edition. New York: Macmillan Publishing Company, 1984.

Fell, J. and J. Hill. Sample Levels for Hardwood Kiln-Drying Control. Forest Products Journal, Vol. 30, No. 3. Pages 32-36, March, 1980.

Holmes, S. and D. Arganbright. Drying Tests with a Weight-Actuated Lumber-Drying System. Forest Products Journal, Vol. 26, No. 11. Pages 31-39, November, 1976.

James, W. L. Dielectric Properties of Lumber Loads in a Dry Kiln. USDA, Forest Service, Research Paper FPL 436. 16 pages, 1983.

Dry Kilns. Southern Lumberman. Pages 14-22, February, 1987.

Little, R. L. KILN-COMP. University of Tennessee, Knoxville, 1985.

Little, R. L., W. W. Moschler, and R. L. Toennisson. Design of a computer based controller-recorder for an experimental dry kiln. Forest Products Journal, Vol. 36, No. 11/12. Pages 72-74, November/December, 1986.

Mcillen, John M. and Eugene M. Wengert. Drying Eastern Hardwood Lumber. U.S.D.A., Agriculture Handbook No. 528, September, 1978.

Meric, A., R. Lessard, Yau-Sen Chiu, V. Azzi, and J. Hill. A Computer Assisted Process Control System for Kiln Drying Hardwood Lumber. Second Annual Hardwood Symposium Proceedings, Hardwood Research Council. Pages 163-190, 1974.

Noffsinger, J. Continuously Rising Temperature (CRT) Drying Process and Some Investigations into Its Use for Drying Eastern Hemlock Studs. Forest Products Research Society, News-Digest, G-1.12. 4 pages, August, 1976.

Rasmussen, Edmund, F. Dry Kiln Operators Manual USDA, Agriculture Handbook No. 188, March, 1961.

Resch, H. and B. Ecklund. Cam-Operated Kiln Control System. Forest Products Journal, Vol. 17, No. 8. Pages 39-42, August, 1967.

Rosen, H. Empirical Model for Characterizing Wood Drying Curves. Wood Science, Vol. 12, NO. 4. Pages 201-206, April, 1980.

Shottafer, J. E. and C. E. Shuler. Estimating Heat Consumption in Kiln Drying Lumber. Life Sci. Agri. Expt. Sta., Tech. Bull. 73, Univ. of Maine, Orono, Maine, 1974.

Simpson, W. and J. Tschernitz. Time, Costs and Energy Consumption for Drying Red Oak Lumber as Affected by Thickness and Thickness Variation. Forest Products Journal, Vol. 30, No. 1. Pages 23-28, January, 1980.

Toennisson, R. L. Energy Use in Lumber Dry Kilns. Tennessee Valley Authority, Forest Resources Development, Norris, Tennessee, Unpublished, 1981.

Tschernitz, J. and W. Simpson. Drying Rate of Northern Red Oak Lumber as an Analytical Function of Temperature, Relative Humidity, and Thickness. Wood Science, Vol. 11, No. 3. Pages 202-208, April, 1979.

Wengert, E. M. How to Reduce Energy Consumption in Kiln-Drying Lumber, USDA, Forest Products Laboratory, Madison, Wisconsin, 1974.

Wengert, E. and P. Evans. Automatic Programing and Control for Steam-Heated Lumber Dry Kilns. Forest Products Journal, Vol. 21, No. 2. Pages 57-59, Febuary, 1971.

APPENDIX

CRANE & CO BOND DALTON MASS

DATA CONVERSION COMPUTER PROGRAM

```
80 OLDTIME = 0:OLDDBSET=0:OLDWBSET=0:OLDKDB=0:OLDKWB=0:LASTU=0
90 '       DATA Conversion Program
100 '        UT Kiln data to TVA averages
110 '
120 '          Feb. 1987,  Rick Toennisson
130 '           TVA - Forestry, Norris, Tn.
140 '           Graduate Thesis Work
150 '
160 '
170 '
180 '
190 WIDTH "LPT1:",132
200 'OPEN "LPT1:" FOR OUTPUT AS #4
210 PRINT  "THE PROGRAM IS RUNNING"
220 '    OPEN THE DATA FILE "DRY.DATA"
230 OPEN "A:timest01.DAT" FOR INPUT AS #3
240 OPEN "A:dry.DAT" FOR INPUT AS #1
250 OPEN "B:STEP1.DAT" FOR OUTPUT AS #2
260 ' INPUT #1,SCHSPC,SCHTHK,SDATE$,LWTOD,STARMC
270 INPUT "FROM RECORD NUMBER";K
280 INPUT "TO RECORD NUMBER";J
290 INPUT #1,STARMC
300 OLDMC=74.1
310 LPRINT "DATA FROM CONTROL RUN"
320 LPRINT "Dry Set  Wet Set Kiln DB Kiln WB   EMC   Thous BTU Load Wgt  Load CD
W":LPRINT "MC WAG  MC SM  MC CAL  ETIME  TIME  MC Ra
te/Day"
330 FOR I=1 TO J
340 ADDE = 0
350 ' INPUT #1,STARMC
360 INPUT #3,ETIME,MC
370 ' TIME EQUATES FOR DOWN TIME
380 IF ETIME > 192.6 THEN ETIME = ETIME + 23.8
390 ' RECORDED TIME 210.8 HOURS
400 IF ETIME > 234.6 THEN ETIME = ETIME + 1.4
410 ' RECORDED TIME 358.11 HOURS
420 IF ETIME > 383.31 THEN ETIME = ETIME + .8
430 INPUT #1,DBSTPT,WBSTPT
440 INPUT #1,KDBTAVE,WBTAVE,KEMCAVE,KPDAVE,KAFAVE
450 INPUT #1,SPRESAVE,SFLOWAVE,SDBTAVE
460 INPUT #1,VAFAVE,VDPTAVE,KAHAVE
470 IF I>1 GOTO 500
480 INPUT #1,ADBTAVE,ADPTAVE,ARHAVE,AAHAVE,AEMCAVE$
490 GOTO 570
500 INPUT #1,ADBTAVE,ADPTAVE,ARHAVE,AAHAVE,M$
510 '
520 ' negative sign elimination
530 IF M$ = " -" THEN GOTO 560
540 AEMCAVE$ = M$
550 GOTO 570
560 INPUT #1,AEMCAVE$
570 INPUT #1,LWTCAVE,WAGMCAVE,MCWTAVE,LOADMCAVE
```

```
720 INPUT #1,VENTTIME,HEATTIME,SPRAYTIMR,SUPVENT
730 ' INPUT #1,VENTTIME$
740 'IF I = 1 THEN LOADODW = LWTCAVE / (1+(MC/100))
750 IF I = 1 THEN LOADODW = 2198.38
760 IF I<K THEN GOTO 790
770 ' PRINT     SPRESAVE,SFLOWAVE,SDBTAVE,I
780 GOSUB 1340
790 IF I>1 GOTO 850
800 '
810 GOSUB 1340
820 X$= SPACE$(1)
830 'Calculations for the New File
840 IF SPRESAVE = 0 THEN U3 = LASTU
850 TIME = ETIME - OLDTIME
860 BTUH = SFLOWAVE * U3: STEAMTIME = HEATTIME + SPRAYTIMR
870 IF STEAMTIME => 100 THEN STEAMTIME = 100
880 ADDE = BTUH * ETIME * ((STEAMTIME)/100)
890 ENERGY = ENERGY + ADDE: MBTUS = ENERGY / 1000
900 WETB = WETB + WBTAVE: DRYB = DRYB + KDBTAVE: COUNT=COUNT+1
910 ' Calculated MC at Reacing
950 'NEWMC = ((LWTCAVE/LOADODW)-1)*100
920 NEWMC = ((LWTCAVE/LOADODW)-1)*100
930 'Calculatec Drying Rate per Day
940 'Equates to last record - Eliminates redundant Records
950 IF WBTAVE = OLDKWB OR KDBTAVE = OLDKDB THEN GOTO 1170
960 DELTAWB = OLDKWB - KWBTAVE
970 DELTADB = OLDKDB - KDBTAVE
980 IF DELTAWB < -1 OR DELTADB < -1 THEN GOTO 1000
990 IF DELTAWB <= 1 OR DELTADB <= 1 THEN GOTO 1170
1000 ENERGY = ENERGY + ADDE
1010 'Calculatec Drying Rate per Day
1020 MCRATE = (OLDMC - NEWMC) / TIME * 24
1030 'MC equates for Control Change
1040 MCWTAVE = MC: LOADMCAVE = NEWMC
1050 KDBTAVE = DRYB / COUNT: WBTAVE = WETB / COUNT
1060 PRINT #2,USING"####.## ";DBSTPT;WBSTPT;KDBTAVE;WBTAVE;KEMCAVE;
1070 PRINT #2,USING"######.## ";MBTUS;LWTCAVE;LOADODW
1080 PRINT #2,USING"###.## ";WAGMCAVE,MCWTAVE,LOADMCAVE,ETIME,TIME,MCRATE
1090 PRINT USING"####.## ";DBSTPT;WBSTPT;KDBTAVE;WBTAVE;KEMCAVE;
1100 PRINT USING"######.## ";MBTUS;LWTCAVE;LOADODW
1110 PRINT USING"###.## ";WAGMCAVE,MCWTAVE,LOADMCAVE,ETIME,TIME,MCRATE
1120 LPRINT USING"####.## ";DBSTPT;WBSTPT;KDBTAVE;WBTAVE;KEMCAVE;
1130 LPRINT USING"######.## ";MBTUS;LWTCAVE;LOADODW
1140 LPRINT USING"###.## ";WAGMCAVE,MCWTAVE,LOADMCAVE,ETIME,TIME,MCRATE
1150 OLDTIME=ETIME:OLDDBSET=DBSTPT:OLDWBSET=WBSTPT:OLDKDB=KDBTAVE:OLDKWB=WBTAVE
1160 LASTU = U3:COUNT=0:WETB=0:DRYB=0:OLDMC=NEWMC
1170 NEXT
1180 CLOSE #1,#2
1190 PRINT "IT'S ALL DONE";
1200 BEEP
1210 END
```

```
1340 'Computation of btus based on table extrapilation
1350 'between t=240, p=14.7 and t=280, p=40
1360 'The recorded pressure is a Gauge reading
1370 ' This subroutine is based on a Superheated vapor chart appearing in
1380 ' "Fundamentals of Classical Thermodynamics" page 654.
1390 PD=20:TEMPDIF=40:P1=0
1400 IF SPRESAVE (= 5.304 THEN PD=5.304
1410 ' Select temperatures and internal energy
1420 T=240
1430 IF SDBTAVE =( 280 THEN A=1087.9
1440 IF SDBTAVE =( 280 THEN A2=1086.5
1450 IF SDBTAVE =( 280 THEN A3=1092.3
1460 IF SDBTAVE =( 280 THEN B=1102.4
1470 IF SDBTAVE =( 280 THEN B2=1101.4
1480 IF SDBTAVE =( 280 THEN B3=1097.3
1490 IF SDBTAVE ) 280 AND SDBTAVE =( 320 THEN T = 280
1500 IF SDBTAVE ) 280 AND SDBTAVE =( 320 THEN A=1102.4
1510 IF SDBTAVE ) 280 AND SDBTAVE =( 320 THEN A2=1101.4
1520 IF SDBTAVE ) 280 AND SDBTAVE =( 320 THEN A3=1097.3
1530 IF SDBTAVE ) 280 AND SDBTAVE =( 320 THEN B=1116.8
1540 IF SDBTAVE ) 280 AND SDBTAVE =( 320 THEN B2=1116!
1550 IF SDBTAVE ) 280 AND SDBTAVE =( 320 THEN B3=1112.8
1560 IF SDBTAVE ) 320 AND SDBTAVE =( 360 THEN T = 320
1570 IF SDBTAVE ) 320 AND SDBTAVE =( 360 THEN A=1116.8
1580 IF SDBTAVE ) 320 AND SDBTAVE =( 360 THEN A2=1116!
1590 IF SDBTAVE ) 320 AND SDBTAVE =( 360 THEN A3=1112.8
1600 IF SDBTAVE ) 320 AND SDBTAVE =( 360 THEN B=1131.2
1610 IF SDBTAVE ) 320 AND SDBTAVE =( 360 THEN B2=1130.6
1620 IF SDBTAVE ) 320 AND SDBTAVE =( 360 THEN B3=1128!
1630 IF SDBTAVE ) 360 AND SDBTAVE ( 400 THEN T = 360
1640 IF SDBTAVE ) 360 AND SDBTAVE ( 400 THEN A=1131.2
1650 IF SDBTAVE ) 360 AND SDBTAVE ( 400 THEN A2=1130.6
1660 IF SDBTAVE ) 360 AND SDBTAVE ( 400 THEN A3=1128!
1670 IF SDBTAVE ) 360 AND SDBTAVE ( 400 THEN B=1145.6
1680 IF SDBTAVE ) 360 AND SDBTAVE ( 400 THEN B2=1145.1
1690 IF SDBTAVE ) 360 AND SDBTAVE ( 400 THEN B3=1143!
1700 ' Select the Pressure Colume
1710 IF PD=5.304 THEN TT=A
1720 IF PD=5.304 THEN TT2=A2
1730 IF PD=5.304 THEN TTH=B
1740 IF PD=5.304 THEN TTH2=B2
1750 IF PD=20 THEN TT=A2
1760 IF PD=20 THEN P1=5.304
1770 IF PD=20 THEN TT2=A2
1780 IF PD=20 THEN TTH=B2
1790 IF PD=20 THEN TTH2=B3
1800 'Extrapolate between the temperature and pressure points
1810 RATE1 = (SDBTAVE - T) / TEMPDIF
1820 U1 = (TTH - TT) * RATE1: U2 = (TTH2 - TT2) * RATE1
1830 U12 = U1 + TT : U22 = U2 + TT2
1840 RATE2 = (SPRESAVE - P1) / PD
1850 U3 = ((U22 - U12) * RATE2) + U12
1860 ' PRINT  "The Btu content per pound is ";U3;U12;U22
1870 RETURN
```

VITA

Richard Lee Toennisson was born in Hamilton, Ohio on April 25, 1953. He attended city schools from elementary through high school and graduated from Taft Senior High School in June 1971. The following March he entered Miami University at the Hamilton campus in preparation for a forestry technician program at the University of Kentucky. In August, 1973 he transferred to the University of Kentucky and received an Associate of Applied Science in Forest Technology in June 1974. He was employed the same month as a forestry technician by the Tennessee Valley Authority at Norris, Tennessee.

The author returned to college, part time, at the University of Tennessee in March, 1976. He was awarded a Bachelor of Science degree in Forest Resource Management in December, 1979. He was promoted by the Tennessee Valley Authority to forester in 1980. In 1983, the author entered The Graduate School of the University of Tennessee. He is a member of the Society of American Foresters, the Forest Products Research Society, and the Tennessee Valley Dry Kiln Association. He has also authored or co-authored several published papers and articles on lumber drying and forest products. He is currently employed by the Tennessee Valley Authority as a Wood Products Engineer.