MATHEMATICAL MODEL FOR CONTROL OF HIGH TEMPERATURE DRYING OF SOUTHERN YELLOW PINE DIMENSION LUMBER

by

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(ABSTRACT)

Although High temperature drying (HTD) of southern yellow pine (SYP) is extensively used, quality problems still exist. Approximately 25 percent of all green lumber (2 x 4, 2 x 6 and 2 x 8's) are degraded during HTD. Warp degrade, specifically "crook", is the main cause for the loss of quality of SYP dried at temperatures above the boiling point of water.

One of the major causes of warp degrade is excessive shrinkage that results from overdrying. In industrial practices, average final moisture contents for HTD of SYP lumber are usually well below the 15% MC maximum permitted by the grading rules. Overdrying the lumber

causes not only lumber quality problems, but also constitutes a waste of energy. In order to improve the overall results of HTD of SYP, it is necessary to perform a better control of the process, so unnecessary extended drying can be prevented.

In this study, a mathematical model based on the temperature drop across the load (TDAL) concept was proposed. The model relates TDAL to drying rates and according to the results, it appears to be an important alternative for controlling purposes during HTD of SYP.

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CHAPTER ONE

INTRODUCTION

Among all processes that exist today for drying wood, high temperature drying (HTD), although an old technique, has been a subject of great interest of many researchers especially during the past fifteen years because of the favorable economic potential of the process. In high temperature drying, the dry-bulb temperature is usually maintained above the boiling point of water. It is common practice for southern yellow pine (SYP) dimension lumber to use dry-bulb temperatures between 110 and 115 °C (230 °F and 240 °F).

In its earlier stages of development, HTD did not produce acceptable quality of the material being dried (Lowery et al. 1968). The main problems were the discoloration of the wood and the development of steep moisture content gradients which resulted in severe casehardening. In addition, the severe conditions of temperature, along with high humidity and acidic atmosphere due to the acids normally released from the wood during high temperature drying, resulted in rapid deterioration of the structure and kiln components.

Although HTD was potentially an important drying process because of its fast drying rates, these initial difficulties in controlling lumber quality and avoiding equipment deterioration constituted the main obstacles for its acceptance by the wood industry.

From those early trials until about fifteen years ago, air drying followed by normal kiln drying was the dominant technique for drying SYP dimension lumber. This method was much more conservative than HTD with respect to drying rates. However, on the other hand, there was a very good quality and there were few deterioration problems with the equipment. Substantial changes in the economy over the past 15 years have influenced many researchers and wood industries to investigate alternative methods for drying SYP dimension lumber. One method that was included was high temperature drying. High temperature drying was especially attractive because of the faster drying rates and therefore reduced drying time, which could be expected to reduce overall drying costs. Koch (1971), for example, compared high temperature drying to normal kiln drying for SYP dimension lumber (2 inches by 4 inches by 8 feet long). He found that the total drying time for high temperature drying was less than 28 hours while normal temperature kiln drying was 113 hours. Wengert (1976) estimated that the total cost for drying southern yellow pine dimension lumber using a twenty-four hour temperature drying schedule was $18.90 per thousand board feet (1000 board feet = 2.4m^3). The total cost for a seventy-two hour normal temperature kiln drying schedule was $22.70 per thousand board feet.

Bois (1976) pointed out ten years ago that high temperature drying of southern yellow pine dimension lumber was rapidly becoming an important drying alternative. Today, high temperature drying of southern yellow pine dimension lumber is commonplace in the South[(1)]. Improved operating procedures (i.e., kiln schedules) have reduced degrade to more acceptable levels. Aluminum prefrabicated kiln wall construction has nearly eliminated equipment deterioration problems.

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(1) Information obtained in July, 1985 from Dr. Eugene M. Wengert, VPI and SU, Blacksburg Va.

Some serious drying quality problems still exist in industrial operations today. Wengert (1984a) states that in one southern pine mill, approximately 25 percent of all green dimension lumber (2 x 4, 2 x 6, and 2 x 8's) was degraded in drying or required trimming after drying to maintain grade . He notes that warp, specifically crook, was the major degrading factor. If it is assumed that lumber is degraded from No. 2 to No. 3, then the overall price reduction, according to November, 1984 market values ,will be approximately $90 per thousand board feet. Dropping from No. 2 to No. 4 is a price reduction of $165 per thousand board feet.

With ten billion board feet of southern yellow pine dimension lumber consumed in the United States in 1983 (NFPA, 1984) and with the estimated degrade and drying costs mentioned above, the economic importance of improving the drying of southern yellow pine dimension lumber can be seen.

One of the major causes of warp degrade is excessive shrinkage that results from overdrying. This was confirmed by Kuhnau and Erickson (1976) who reported that drying degrade that occurred during high temperature drying of southern yellow pine dimension lumber was strongly related to final moisture content. They estimated a loss of over $2 per thousand board feet for each one percent MC that the lumber was overdried below 15% MC. In industrial practice today, average final moisture contents for HTD SYP lumber are usually well below the 15% MC maximum permitted by the grading rules[2]. These low averages are desired to assure that nearly all of the individual pieces of lumber in the kiln will be at a moisture content not higher than 15% MC. Overdrying the lumber causes not only lumber quality problems, but also constitutes a waste of energy.

According to Oliveira and Wengert (1984), uniform final moisture contents are expected to greatly reduce degrade losses during high temperature drying. Therefore, in order to improve the overall results of high temperature drying of southern yellow pine, this dissertation will show how drying conditions inside a high temperature dryer can be measured and controlled in order to prevent excessively low and non-uniform final moisture contents.

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(2) Much of the SYP dimension lumber manufactured is marketed at MC15, which requires the lumber to be below 15% MC.

CHAPTER TWO

HYPOTHESIS

The key to any lumber drying process is to optimize the drying rate while not having excessive degrade, energy use or cost. During high temperature drying (HTD) of lumber, a complex interaction between heat transfer, mass transfer and the physical characteristics of the lumber being dried (anatomical structure, permeability, moisture content and size) influences the rate of water removal throughout the drying process.

Drying rate responses to the simultaneous heat and mass transfer will be adequately predicted if transport phenomena during drying and their associated resistances can be described in a relatively simple mathematical form that can be used for modeling purposes. Therefore, the general hypothesis for the overall research area is that if drying rate can be accurately predicted throughout the lumber pile during high temperature drying of southern yellow pine dimension lumber, then this information can be used to describe the drying process and thereby improve uniformity of the drying conditions and avoid overdrying[3]. As a direct result, drying quality will be improved and energy will be saved.

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(3) From a producer's viewpoint, the average final moisture content should be as high as possible (i.e. close to the 15% moisture content required) to avoid warp degrade. However, the consumer would like to have lower moisture contents (close to the equilibrium moisture content in use), so that warping during wood utilization will not occur.

CHAPTER THREE

OBJECTIVES

The objectives of this research were:

1- To develop a mathematical model that can be used to predict drying rates of green southern yellow pine dimension lumber (2 x 4's) dried at a dry-bulb temperature of 115 °C and a wet-bulb temperature varying between 50 °C and 70 °C with air velocities through the load of lumber of approximately 200 cm/s, and to develop expressions that can be used to predict wood surface temperature during drying.

2- To compare magnitudes of heat and mass transfer during high temperature drying of southern yellow pine dimension lumber.

3- To describe the principles of a kiln control system based on temperature drop across the load (TDAL) concepts.

CHAPTER FOUR

REVIEW OF THE LITERATURE

A. High Temperature Drying of Softwoods

Kollmann and Cotê (1968) showed that green softwood one-inch thick could be high temperature dried to a final moisture content of 10%. However, due to the severe conditions imposed by the high temperature drying process, there was some collapse.

Kimball and Lowery (1967) conducted research to compare high temperature drying to normal kiln drying of lodgepole pine and western larch 2x4 studs. Their results are summarized:

a) There was a greater variation in final moisture content for the studs dried at high temperatures;

b) High temperature drying produced steeper moisture gradients during and after drying;

c) More residual stresses were found in studs dried at high temperature;

d) More end checks were found in the studs dried at high temperatures.

Kozlik (1967) studied high temperature drying of Douglas fir dimension lumber (2 x 4, 2 x 6, and 2 x 8's). He indicated that when 2 by 8-inches dimension lumber was subjected to high temperatures in the initial stages of drying, serious degrade such as surface checks and honeycomb occurred. He also noted that for the 2 x 4 and 2 x 6's that high temperature drying did not result in any serious quality problems. Average moisture contents were reduced from the green condition to approximately 15% in 50 hours and 28 hours respectively.

Studies conducted in Australia by Gough (1974) indicated that slash pine (Pinus elliottii) 75 x 50 cm in cross section could be successfully dried at a dry-bulb temperature of 121 °C and at a wet-bulb temperature of 71 °C. With stickers 29 mm thick and an average air velocity of 4.3 m/s through a stack 0.9 m wide, he observed that final moisture contents ranged between 7% and 13%. Using the same conditions for a wider stack (1.5 m), final moisture contents varied between 8 and 23%.

Christensen and Mackay (1972) reported that one-inch (2.54 cm) radiata pine could be successfully dried at high temperatures in commercial kilns as long as 7/8-inch (2.2 cm) thick stickers were used to separate boards; the stack width was six feet wide (1.8 m), and an air velocity of 600 ft/min (3 m/s) was uniformly maintained throughout the pile.

Salamon (1973) studied high temperature drying of spruce (Picea spp.) 2 inches thick (5.1 cm) with lumber widths between 6 to 12 inches (15.2 to 30.5 cm). In his study, he carried out experiments to evaluate several different kiln schedules:

- a normal kiln drying with dry- and wet-bulb temperatures ranging between 165 °F to 175 °F (73.9 °C to 79.4 °C) and 155 °F to 170 °F (68.3 °C to 76.7 °C) respectively;

- a combination low - high temperature drying schedule with dry-bulb temperatures ranging between 170 °F and 232 °F (76.7 °C and 111.1 °C) and wet-bulb temperatures between 160 °F to 205 °F (71.1 to 96.1 °C);

- a low-high temperature schedule with a constantly increasing dry- and wet-bulb temperatures up to 265 °F and 205 °F respectively (129.4 °C and 96.1 °C);

- a constant high temperature drying schedule with a dry-bulb of 232 °F (111.1 °C) and wet-bulb of 205 °F (96.1 °C); and

- a superheated steam schedule with a dry-bulb temperature of 230 °F (110 °C) and a wet-bulb temperature of 212 °F (100 °C).

The total drying time for the normal kiln drying schedule was 74 hours with an average drying rate of 0.40 % MC/h, the constant high temperature drying schedule required 42 hours with an average drying rate of 0.72 % MC/h, and the superheated-steam drying schedule required 40 hours with an average drying rate of 0.61 % MC/h. Air velocity was 250 ft/min (1.3 m/s) in all experiments except for the second low-high temperature drying schedule which had air velocities from 250 ft/min to 900 ft/min (1.3 m/s to 4.6 m/s). With air velocities of 900 ft/min (4.6 m/s), drying rates were increased 33% for the low-high temperature drying schedule. Final moisture contents in all experiments averaged 11.5% MC and varied between 7.6% and 17.4% MC. The low-high temperature schedule with maximum dry-bulb temperature of 265 °F (129.4 °C), the constant high temperature schedule, and the superheated-steam schedule produced an excessive amount of honeycomb.

He also showed that a combination of high air velocities and low dry-bulb temperatures in the beginning of the drying process changing to lower air velocities with dry-bulb temperatures above the boiling point of water during the latter part of the drying process could increase the overall drying rate without inducing serious degrade.

Rosen (1978) jet-dried southern yellow pine and Douglas fir 1.75 inches thick (4.4 cm) at temperatures varying from 160 °F to 400 °F (71.1 °C to 204.4 °C) and air velocities ranging from 3,000 to 9,000 ft/min (15.3 m/s to 45.7 m/s). He reported that southern yellow pine can be successfully jet-dried in less than 15 hours Honeycomb and end-checking were the main problems during jet-drying.

Koch (1971) dried southern yellow pine under restraint at high temperatures for 24 hours and observed that warp represented by crook, bow and twist was significantly reduced compared to unrestrained lumber. He suggested that to achieve effective warp reduction by restraint, a top load of 200 pounds per square foot should be used (977.2 kg/m^2).

In another study (Koch 1974), moderate to severe end-checking in southern yellow pine three and four inches thick was observed. Although infrequent, some internal checks were observed in the lumber four inches thick (10.2 cm).

Comparing high temperature drying of southern yellow pine dimension lumber (2 x 4's) to a milder schedule in which dry-bulb temperatures were below 180 °F (82.2 °C), Koch (1971) found that the total drying time in high temperature drying was 24 hours, while for the low temperature schedule total drying times ranged between 102 and 113 hours.

After several years of research on high temperature drying of southern yellow pine dimension lumber, Koch (1984) designed a drying schedule for 2 by 4 studs of dry- and wet-bulb temperatures of 240 °F (115.6 °C) and 160 °F (71.1 °C) respectively for 21 hours. In order to complete the schedule, Koch suggested a 3-hour conditioning period in which the dry-bulb temperature would be maintained at 195 °F (90.6 °C), while the wet-bulb temperature would be set at 185 °F (85 °C).

B. Energy

Drying of wood is intrinsically an energy intensive process. Sixty to 70% the total energy consumed in the lumber production industry, is for the drying operation (Skaar 1977).

Lowery et al. (1968) indicated that lower energy requirements for HTD is one of its main advantages. According to Kauman (1956), heat economy is even favorable in a superheated steam atmosphere due to the inherent higher efficiency of water evaporation under such condition. Wengert and Lamb (1983) reported that 40% to 50% less energy is required during high temperature drying when compared to normal kiln drying. Although larger heating system capacity is higher for high temperature drying (Wengert and Lamb 1983), the total steam consumption can be 30% to 50% lower when compared to normal kiln drying (Christensen and Mackay 1972).

Koch (1971) compared energy consumption between a high temperature drying schedule and a low temperature drying schedule [maximum dry-bulb temperature of 180 °F (82.2 °C)] when drying southern yellow pine dimension lumber (2 x 4's). He found that for the high temperature drying schedule, the total energy consumption varied from 551 kWh to 618 kWh while for the low temperature drying schedule, the total energy consumption ranged from 1,102 kWh to 1,199 kWh.

According to Rosen (1979), the energy required during drying depends on the ratio of the total kiln surface area to the volume of wood. As kilns have a large surface area to lumber volume ratio, high energy losses through the wall (compared to the energy for evaporation) are observed. In comparison, in large kilns with smaller area to volume ratio, energy losses through the wall are not a large part of the overall energy requirements. Therefore, kiln surface area to volume of wood must also be considered comparing energy consumption between high temperature kilns and normal temperature kilns.

Taylor (1982) compared energy consumption when drying southern yellow pine dimension lumber with three different schedules: dry-bulb of 240 °F (115.6 °C); dry-bulb of 190 °F (87.8 °C); and a variable temperature schedule in which dry-bulb temperatures ranged from 165 to 175 °F (73.9 °C to 79.4 °C). His results indicate that an average of 2,070 Btu per pound of water removed (1.3 kWh/kg) was required during the high temperature drying process and this was 12 and 15% less energy when compared to the energy requirements for the 190 °F (87.8 °C) drying schedule and for the variable drying schedule respectively.

C. Physical and Mechanical Properties

A great amount of work on high temperature drying of softwoods has attempted to determine possible effects on physical and mechanical properties of lumber. Much of the concern has resulted directly from the fact that wood that would be dried under a high temperature schedule would often be utilized as dimension lumber for structural purposes.

According to Hillis (1984) the heating of wood will induce changes in the nature of the wood components (cellulose, hemicellulose, lignin and extractives). Therefore, physical properties such as hygroscopicity, stability and permeability would be altered.

Koch (1976) states that a reduction of mechanical properties of southern yellow pine dimension lumber dried at 240 °F (115.6 °C) "is not of practical significance". Subsequently, Price and Koch (1980) investigated the influence of kiln residence time and temperature on No. 2 Dense 2 x 6 southern yellow pine. They conducted a series of experiments at 180 °F (82.2 °C), 240 °F (115.6 °C) and 270 °F (132.2 °C). In all experiments, the wet-bulb was maintained at 160 °F (71.1 °C). Kiln residence times were 120 hours at 180 °F (82.2 °C); 36 hours and 120 hours at 240 °F (115.6 °C); and 9 hours, 36 hours and 120 hours at 270 °F (132.2 °C). With the exception of the kiln residence time of 120 hours at both 240 °F (115.6 °C) and 270 °F (132.2 °C), the authors did not find a significant difference in mechanical properties such as rupture modulus, proportional limit, elasticity modulus, compression strength parallel to the grain, hardness and toughness. Boards dried at 240 °F (115.6 °C) and 270 °F (132.2 °C) for 120 hours had reduced rupture modulus and toughness values.

Therefore, as pointed out by Koch (1984), although mechanical properties of southern yellow pine dimension lumber are diminished due to exposure to temperatures above the boiling point of water, it seems that the effects on mechanical properties do not constitute a serious problem due to the fact that the lumber is usually exposed for a relatively short period of time to high temperatures during the drying process. (that is, wood temperature is much below the dry-bulb temperature).

D. Wet-bulb Temperatures

Only few studies dealing with the effects of wet-bulb temperatures on high temperature drying of wood have been reported in the literature. Rosen and Bodkin (1981) observed that the effect of wet-bulb temperature on drying rates of yellow-poplar was less at dry-bulb temperatures above the boiling point of water than below. According to Rosen (1977), drying rates are not greatly affected by wet-bulb temperatures during high temperature drying of lumber.

Koch (1972a) dried southern yellow pine studs (4.8 cm thick) using dry-bulb temperature of 240 °F (115.6 °C) and wet-bulb temperatures of 125 °F (51.7 °C), 160 °F (71.1 °C) and 200 °F (93.3 °C). He indicated dry- and wet-bulb temperatures of 240 °F (115.6 °C) and 160 °F (71.1 °C) respectively, provided faster drying than the other schedule combinations, requiring a total drying time of 20.7 hours. There was no evidence in his study explaining why there were differences in drying rates among the process utilized.

Vermaas and Wagner (1983) reported that drying Pinus radiata and Pinus patula at a dry-bulb temperature of 266 °F (130 °C), wet-bulb temperatures varying between 131 °F (55 °C) and 185 °F (85 °C) had no effect on drying rates. However, when drying was carried out at dry-bulb temperatures of 230 °F (110 °C), they observed that drying rates were increased with increased wet-bulb temperatures.

Therefore, from the studies found in the literature, it seems that the effect of wet-bulb temperatures on drying rates in high temperature drying of lumber is not yet well established.

E. Convective Heat Transfer Coefficients

Only a few attempts have been made to determine convective heat transfer coefficients during the drying of wood. An early study conducted by Stevens et al. (1956) related the average convective heat transfer coefficient (h) to air velocity through a lumber pile. The experiment was carried out at a dry-bulb temperature of 140 °F (60 °C) and at wet-bulb temperature of 122 °F (50 °C). Air velocities through the lumber pile ranged from 1.5 ft/s to 8 ft/s (0.5 m/s to 2.4 m/s). The following relationship was obtained:

$$h = 1.9 + 0.48v \qquad \text{...(Eq.1)}$$

where h is expressed in Btu/(ft^2 h °F) and v is the average air velocity through the lumber pile in ft/s. In this study the authors calculated h values varying from 2 Btu/(ft^2 h °F) to 7 Btu/(ft^2 h °F) (9.8 Kcal/m^2 h °C to 34.2 Kcal/m^2 h °C).

Lyman (1965) performed experiments to study heat transfer coefficients in air-impingement systems. He suggested that heat transfer coefficients in absence of mass transfer were related to air mass flow :

$$h_{avg} = C_1(v)^n \qquad \text{...(Eq.2)}$$

$$h_{avg} = C_2(G)^m \qquad \text{...(Eq.3)}$$

In these expressions C_1, C_2, m and n are experimentally determined coefficients and v and G are air velocity (ft/min) and mass air flow (lb/ft^2h) respectively. From analysis of the experimental data, the author determined a value for n equal to 0.6439 and a value for m equal to 0.6912. Values for coefficient C_1 varied between 0.0638 and 0.1277 and C_2 ranged between 0.3004 and 0.7277. These variations were due to the orifice area and vertical spacing of the air impingement system. With air velocities varying from 4,800 ft/min (24.4 m/s) to 20,000 ft/min (101.6 m/s), Lyman obtained heat transfer coefficients ranging from 14 Btu/(ft^2 h °F) (68.3 Kcal,m^2 h °C) to 78 Btu/(ft^2 h °F) (380.2 Kcal/m^2 h °C).

Chromcharm and Skaar (1983) estimated an h value of 4.5 Btu/(ft^2 h °F) (22 Kcal/m^2 h °C) when drying round wafers of green basswood at 77 °F (25 °C) and 77% relative humidity. They pointed out that the determined heat transfer coefficient of 4.5 Btu/(ft^2 h °F) was within the range predicted by the relationship proposed by Stevens et al. (1956).

Beard et al. (1984) described a method to determine heat coefficients during wood drying using temperature distributions inside the wood. In their experiment, yellow-poplar samples approximately 12 inches (30.5 cm) long by 2 inches (5.1 cm) thick were dried according to two drying schedules. In the first drying schedule the wood samples were dried at a dry- and wet-bulb temperature of 300 °F (148.9 °C) and 180 °F (82.2 °C) respectively. The second drying schedule had a dry- and wet-bulb temperatures of 250 °F (121.1 °C) and 131 °F (55 °C). For the first schedule they found an average heat transfer coefficients was 8.3 Btu/(ft^2 h °F) (40.5 kcal/m^2 h °C); for the second, the average was about 9.4 Btu/(ft^2 h °F) (45.9 Kcal/m^2 h °C).

Plumb et al. (1984) carried out experiments to measure heat and mass transfer during convective drying of southern yellow pine. Utilizing very wet wood (moisture content between 100 and 130% dry basis), they measured heat flow reaching the surface of the wood, temperatures within the wood, and velocity of the air stream in a special laboratory dryer designed to approximate one-dimensional drying. The results were plotted in terms of Nusselt number (Nu) versus Reynolds number (Re). For Prandtl number (Pr) equal to 0.7 and for Reynolds number varying between 10,000 and 100,000, the following was obtained:

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.33} \qquad \text{...(Eq.4)}$$

This empirical relationship agrees to the equation for highly turbulent flow in pipes derived from dimensional analysis presented by Bird et al. (1960).

Bird et al. (1960) indicated that heat transfer coefficients can be affected by the rates of mass transfer, and therefore should be corrected in high intensity mass transfer processes. They showed that mass transfer from a solid phase into a moving fluid, decreases the heat transfer coefficients. The decrease in heat transfer would happen because mass transfer would alter the temperature and velocity profiles in the boundary layer causing an increase in its thickness.

Luikov (1963) performed experiments on evaporation of liquids from free surfaces. He found that heat transfer coefficients were higher during the evaporation process compared to the values determined in the absence of mass flow. In another study, Luikov (1966) presents several curves relating the convective heat transfer coefficients to moisture content during drying of pine wood. His results indicated that the heat transfer coefficient was was constant at 2.7 Btu/(ft^2 h °F) (13.2 Kcal/m^2 h °C) for average moisture contents above 35-40% when drying at dry-bulb temperatures of 240 °F (115.6 °C). Below 35% MC, the heat transfer coefficient decreased to 2.2 Btu/(ft^2 h °F) (10.7 Kcal/m^2 h °C). This is in conflict with the theoretical analysis carried out by Bird et al. (1960).

F. Transport Phenomena During Wood Drying

Convective drying of wood is a complex phenomenon because it involves simultaneous transference of heat and mass.

Usually the drying process at temperatures below 212 °F is divided into three periods (Sherwood 1929). The first period is normally termed as "period of constant drying rate". It will last as long as water can migrate to the surface to be evaporated. During the first drying period, as the surface of the wood is still wet, the temperature for this region will be equal to the wet-bulb temperature. The rates of heat and mass transfer through the boundary layer will control the amount of drying during the constant drying rate period (Lowery et al.

1968). The other two drying stages are termed "falling drying rate periods".

Hart (1975) further hypothesizes that as the surface of the wood dries out, an increase in its temperature is observed. Consequently less energy will reach the surface of the wood as drying proceeds (at constant dry-bulb temperature) because the temperature differential between the air and the surface of the wood is reduced. The diminished amount of energy reaching the surface of the wood results in a reduction in drying rates. The situation described above characterizes the beginning of the falling rate period observed by Sherwood (1929).

According to Hann (1964), high temperature drying of wood can also be divided into 3 drying periods. The results of his studies on press-drying of yellow-poplar can be summarized as follows:

a- During the first drying rate period, the temperature of the wood remained at 100 °C. He indicated that the drying rate was controlled by the rate of heat transfer to the surface of the wood. The first drying period ended when the temperature of the surface of the wood began to increase, indicating that free water was not moving to the surface fast enough to prevent an increase in temperature.

b- During the second drying period, he observed that the temperature in the center of the wood was approximately 100 °C. He indicated that the rate of heat transfer inside the wood was the controlling factor for this drying period. As the second drying stage progressed, Hann hypothesized that steam pressures were building up inside the wood and consequently, drying rates could be favored.

c- The third drying stage was characterized by the assumption that the center of the wood had reached a moisture content below the fiber saturation point (approximately 20% MC for yellow-poplar at 180 °C). He observed that the third drying period was different from the second drying period because temperature gradients decreased. As for the previous drying periods, Hann hypothesized than the rate of heat transfer within the wood, rather that moisture movement, was the controlling factor of the drying process.

The theoretical analysis of transport phenomena during high temperature drying of wood is even more complex than at temperatures below 212 °F due to the mass flow resulted from internal pressure built up during the process.

Hart (1975) hypothesized that as the temperature inside the wood approaches the boiling point of water, pressure is built up and as result, pressure flow of the water toward the surface of the wood will occur. Hart characterized the existence of the pressure flow as the main difference between high temperature drying and normal kiln drying. Hart provides no data to support this theory.

According to Rosen (1984), the mathematical models developed to describe transport phenomena during high temperature drying of wood, usually require many physical parameters that are functions of temperature, moisture content and species. As a result, utilization of such models normally require many simplifications in order to be applied to practical situations.

Lowery (1972) measured internal pressures in Engelmann spruce dried at 180 °F (82.2 °C) 230 °F (110 °C) and 280 °F (137.8 °C). The maximum pressure observed was 1,534 mmHg when drying was carried out at 280 °F (137.8 °C).

Vermaas and Wagner (1983) measured internal pressures during high temperature drying of *Pinus radiata* and *Pinus patula*. The maximum pressure observed was approximately 1,800 mmHg.

Luikov (1966) presents a system of differential equations that describe the simultaneous transport of heat and mass in capillary bodies. In his analysis he describes a filtration flow as direct result of pressure gradients caused by pressure increase of the entrapped air. His mass balance equation takes into consideration not only moisture concentration gradients, but also mass transfer under the influence of a thermal gradient (the Soret effect) and mass transfer due to filtration caused by pressure gradients. It is interesting to note that many wood drying researchers, neglecting thermal and pressure effects on mass transfer, have applied the Fick's second law of diffusion to drying.

As pointed out by Rosen (1984), the transport coefficients that appear in the Luikov equations are strong functions of temperature and moisture content. As this functional relationship is unknown, this is perhaps the most important difficulty in applying Luikov equations.

Permeability is important when considering mass flow that results from pressure gradients during high temperature drying (Hart 1975). Transfer of liquid water occurs through intercellular pitting which are openings in the secondary wall. Drying may induce high capillary forces on the surface of the free water contained in the cells. This in turn may cause pit aspiration (Siau 1984) which will decrease permeability as drying progresses (Siau 1984).

A simplified approach to describe transport phenomena during convective drying has been given by Luikov et al. (1967). Their analysis relating heat and mass transfer related through the law of conservation of energy resulted in an expression relating the amount of energy supplied to heat the moist body and the energy for evaporating water, a dimensionless number, named the "Rebinder number (Rb)". The Rebinder number is defined as :

$$Rb = \frac{C_m \quad dT_{avg}}{L_v \quad dMC_{avg}} \qquad \text{...(Eq.5)}$$

The Rb number is a function of the specific heat of the moist body (C_m), the latent heat of vaporization (L_v) and the thermal diffusivity of the drying process. By relating the Rb number to the average moisture content of the moist body, it is possible to characterize the intensities of heat transfer throughout the drying process (Luikov et al. 1967).

An earlier study external drying conditions were related to the rate of water removal during drying of green wood (Stevens and Johnston 1957). It was observed that as air travels across a lumber pile in an industrial kiln, the dry-bulb temperature decreases indicating that the heat transfer to the lumber surface along the pathway is not constant. They have also observed that the cooling effect is considerably reduced when using higher air velocities through the pile. Another interesting observation from their study is that by reversing the air flow, the average drying rate halfway through the pile was about twice as large (0.04 lb/(ft^2 h) (0.2 Kg/m^2 h) as the drying rate in the same with position unidirectional flow.

G. Approaches To Control Industrial Drying of Wood

Bai and Garrahan (1984) conducted high temperature drying experiments with red pine planks (2 x 6's). Prior to drying, the wood was preheated with steam until the center reached 212 °F (100 °C). Then the dry-bulb temperature was 240 °F (115.6 °C) and wet-bulb temperature was 200 °F (93.3 °C). A total of six thermocouples were placed at equal depth increments (approximately every 0.6 cm) across the thickness of the wood. Except for early in drying, temperature distributions within the wood reflected the moisture content distribution in the wood throughout the drying process. According to variations in internal temperatures of the wood, the authors divided the drying period in two more drying periods in which moisture content decreased exponentially with time and into a transition period.

Regression analysis for the two falling drying rate periods resulted in the following equations:

$$MC_1 = 66.48\ e^{(14.485 - 0.070\ T1)}$$

$$MC_2 = 66.48\ e^{(9.180 - 0.047\ T2)}$$

The first equation was for moisture contents ranging between approximately 20% and 60%, and the second equation was obtained for moisture content values between 10% and 20%. The authors claimed that the severity of moisture content gradients during the drying period change with respect to the corresponding severity of temperature gradients. In addition, average moisture content related well to the temperature in the center of the wood. Based on these findings, they suggested that average moisture content of wood through the high temperature drying process could be estimated by measuring internal temperatures.

Recently an important approach to improve the control of drying during high temperature drying of southern yellow pine dimension lumber was given by Wengert (1984a). He hypothesized that if drying conditions could be closely controlled for different regions inside the kiln, then a more uniform drying environment would be achieved. As a result, all lumber could reach approximately the same final moisture content. In order to evaluate drying rates throughout the dryer, he suggested measuring dry-bulb temperature drop across the load. Using the temperature drop across the load concept, Wengert (1984a) designed and tested a drying system for an industrial kiln. In his design there are 12 zones of heating control for a two-track steam heated kiln with a load of lumber of 8 feet wide. The heating control in each zone is performed by a computerized system according to the temperature drop across the load input information. His results indicated that temperature drop across the load related well to drying rates and average moisture contents, and preliminary tests indicated that rejects have been reduced more than 25%.

CHAPTER FIVE

THEORETICAL ANALYSIS

A. Thermal Resistance

In a typical convective drying operation, the surfaces of the lumber are exposed to currents of a mixture of air and water vapor. Energy transferred from the hot gas-vapor mixture to the lumber (that is, convective heat transfer) must first overcome the external resistance of the boundary layer before entering the wet wood to produce drying.

After energy enters the wood, heat is propagated through the wood by conduction proportional to the temperature gradient (Fourier's Law).

The conductivity (reciprocal of resistance) of heat through the wood decreases as moisture content is decreased (Kollmann and Coté 1968). According to Koch (1972) the resin content of southern yellow pine does not affect thermal conductivity. Kollmann and Coté (1968) presented the following equations relating thermal conductivity and wood moisture content:

$$k_{wwd} = (1.39 + 0.028MC/100)\ G + 0.165 \qquad \text{...(Eq.6)}$$

and

$$k_{wwd} = (1.39 + 0.038MC/100)\ G + 0.165 \qquad \text{...(Eq.7)}$$

where:

k_{wwd} = Thermal conductivity [Kcal m/(m^2 h °C)]

MC = Wood moisture content (%)

G = specific gravity of wood (dimensionless)

Equation 6 is normally used for wood below moisture contents below 40% while Equation 7 is used for moisture contents above 40%.

Both equations above are normally used independently of the wood species. Koch (1972) reports that a deviation of ± 3.2% was found when comparing predicted thermal conductivity to experimentally determined values for loblolly pine.

As can be seen from Equations 6 and 7, resistance to heat flow is higher at lower moisture contents because of the resistance to heat flow of the air within the wood (Koch 1972).

Maku (1954) reported that the physical properties of wood utilized to define thermal conductivity, are influenced by temperature, density, moisture content and direction of the fibers. For example, he reported for Pinus spp, thermal conductivity parallel and perpendicular to the grain of 0.300 Kcal/m h °C and 0.120 Kcal/m h °C respectively.

Density and specific heat capacity of wood are also increased as moisture content increases. According to Siau (1984), density of wood can be expressed by:

$$d_{wwd} = d_{wd}\ (1 + mc) \qquad \ldots(\text{Eq.}8)$$

where:

d_{ww} = Density of wet wood (Kg/m^3)

d_w = Density of water (Kg/m^3)

d_{wd} = Basic density of wood (Kg/m^3)

mc = Fractional moisture content (%MC/100)

For example, considering d_{wd} = 480 Kg/m^3 for southern yellow pine (Wood Handbook 1974), it can be seen from Equation 8 that the density of moist wood will vary from approximately 900 Kg/m^3 to 600 Kg/m^3 when moisture content is decreased from 90% to 30%.

According to Kellog (1981), the specific heat capacity of wood at 0% moisture content can be expressed by:

$$C_{wd} = 0.266 + 0.00116\ T \qquad \text{...(Eq.9)}$$

where C_{wd} is the specific heat capacity of dry wood expressed Kcal/Kg °C and T is the wood temperature expressed in °C. Integrating Equation 9 between 0 °C and 100 °C gives an average value of 0.324 Kcal/Kg °C.

As moisture content increases, specific heat capacity for wood is given by the following equation (Kellog 1981):

$$C_{wwd} = \frac{C_{wd} + mc\ Cp_w}{1 + mc} \qquad \text{...(Eq.10)}$$

where:

C_{wwd} = Specific heat capacity of wet wood (Kcal/Kg °C).

Cp_w = Specific heat capacity of water (Kcal/Kg °C)

If Cp_w is assumed to be 1 Kcal/Kg °C, the specific heat capacity of wood will vary from 0.662 Kcal/Kg °F to 0.324 Kcal/Kg °F when moisture content is decreased from 100% to 0%.

According to Maku (1954) and Kollmann and Coté (1968), changes in thermal diffusivity (k_{wwd}/C_{wwd} d_{wwd}) of wood for practical purposes, can be considered small because variations of the physical properties k_{wwd}, C_{wwd} and d_{wwd} due to changes in moisture content and temperature, are offsetting.

B. Moisture Resistance

During drying of wood, mass transfer resulting from a combination of liquid, water-vapor and bound water movement will be affected by internal and external resistances.

External resistance to mass flow will depend on the conditions of the drying process such as temperature, velocity and relative humidity of the drying medium. Rosen (1984) pointed out that in high temperature drying, the period in which the external drying conditions control the process is too short and difficult to separate from the falling rate period.

Internally, the overall mechanism of mass transfer is rather complicated due to the superimposed transport mechanisms of liquid, vapor and bound water. Although theoretically these different transport mechanisms would be occurring simultaneously, their magnitude and therefore their relative importance for the overall moisture removal, depends upon the amount of water contained in the wood.

Independent of the particular moisture mechanism that is prevailing during a certain stage of the drying process, energy must be supplied in order to evaporate the water within the wood. The overall mass transfer from wood is therefore dependent upon the heat transfer to the surface of the wood as well as the heat transfer through the interior regions of the wood.

C. Lewis Number for Air

In order to better examine simultaneous heat and mass transfer during high temperature drying of wood, it is necessary to provide a quantitative way to establish the magnitude of these two transport phenomena. A very useful concept normally utilized to relate simultaneous heat and mass transfer in the boundary layer, is expressed by the ratio between thermal and mass transfer (Bennet and Myers 1974). This ratio, known as the Lewis number (Le) is given by:

$$Le = \frac{Sc}{Pr} \qquad \text{...(Eq.11)}$$

where Sc is the Schmidt number and Pr is the Prandtl number. The Schmidt and Prandtl numbers are expressed by:

$$Sc = \frac{\mu_{am}}{d_{am}\ D_{wv-a}} \qquad \text{...(Eq.12)}$$

and

$$Pr = \frac{\mu_{am}\ Cp_{am}}{k_{am}} \qquad \text{...(Eq.13)}$$

where:

μ_{am} = Fluid (air and water-vapor) viscosity (g/cm s)

d_{am} = Fluid density (kg/m^3)

D_{wv-a} = Diffusion of water-vapor into air (cm^2/s)

Cp_{am} = Specific heat capacity for the mixture air and water-vapor (Kcal/Kg °C)

k_{am} = Thermal conductivity of the mixture of air and water-vapor (Kcal/m s °C)

According to Welty et al. (1976), the Pr number is a function of temperature and expresses the ratio of momentum diffusivity to molecular diffusivity of heat.

Bird et al. (1960) points out that the Schmidt number for convective mass transfer is analogous to the Prandtl number in heat transfer, and expresses the ratio between momentum diffusivity and mass diffusivity.

For a process such as drying of wood, which involves simultaneous heat and mass transfer, analysis of the Lewis number permits one to establish the relative magnitudes for both mechanisms. For instance, if during a certain period of the drying process the Le number is less than one, then the resistance to heat transfer is greater than resistance to mass transfer. Therefore, heat transfer would be the limiting or retarding factor during the process.

According to Welty et al. (1976), the Sc and Pr numbers for dry air at 65 °F are 0.61 and 0.72 respectively. For this situation the Lewis number is 0.61/0.72 = 0.85 which indicates that resistance to heat transfer is slightly greater than resistance to mass transfer.

The diffusivity of water-vapor into air may be estimated by the following empirical expression (Welty et al. 1976):

$$D_{wv-a}\big|_{T2} = D_{wv-a}\big|_{T1}(T_2/T_1)^{1.5} \qquad \text{...(Eq.14)}$$

where

D_{wv-a} is the diffusivity in cm^2/h, T_1 (°C) is the temperature to which the diffusivity is known and T_2 (°C) is the temperature at which it is desired to estimate the diffusivity.

For example, when air is heated from 80 °C to 100 °C, the viscosity increases about 4% and the density decreases approximately 7% (Bird et al. 1960). However, as can be seen from Equation 14, heating the air from 80 °C to 100 °C will cause an increase in diffusivity of approximately 40%. The overall consequence is that the denominator of Equation 12 (Schmidt number) will increase, resulting in a decrease in the Lewis number. This indicates that at higher temperatures in the boundary layer, the resistance to heat transfer is greater than the resistance to mass transfer.

D. Lewis Number for Wood

With the appropriate modification, the concept of Lewis number can be utilized to relate simultaneous transport phenomena inside the wood. In order to apply the concept expressed by the ratio of diffusivities (thermal diffusivity to mass diffusivity) to transport phenomena during drying of wood, a modified Lewis number can be defined by analogy:

$$Le_{wd} = \frac{\text{Thermal transport inside the wood}}{\text{Mass transport inside the wood}} \quad \text{...(Eq.15)}$$

Equation 15 expresses the relative resistance to heat and mass flow within the wood. Mathematically, Equation 15 can be written as:

$$Le_{wd} = \frac{k_{wwd}}{d_{wwd}\ Cp_{wwd}\ D_m} \quad \text{...(Eq.16)}$$

where

k_{wwd} = Thermal conductivity of wood [Kcal m/m^2 h °C]

d_{wwd} = Density of wet wood (Kg/m^3)

C_{wwd} = Specific heat capacity of wet wood (Kcal/kg °C)

D_m = Coefficient of overall moisture transport (m^2/h)

The coefficient of overall moisture transport (D_m) introduced in Equation 16 corresponds to the combined mass flow of liquid water, water-vapor and bound water that occurs inside the wood during drying. This transport coefficient is equivalent to the diffusion coefficient defined by Fick's first law as shown below:

$$F = -D \frac{dC}{dx} \qquad \text{...(Eq.17)}$$

where:

F = flux of diffusant in g/cm^2 s

C = mass concentration in g/cm^3

x = thickness of wood in cm

D = diffusion coefficient in cm^2/s

Rice (1985) discusses the applicability of using transport equations analogous to Fick's laws in order to describe movement of moisture through a coating applied to saturated wood. Using the appropriate units, the author represented the equations analogous to Fick's first and second laws of diffusion by the following:

$$F = -K \frac{\delta RH}{\delta x} \qquad \text{...(Eq.18)}$$

where:

F = Flow of moisture in kg/m^2 h

K_m = Moisture conductivity (Kg m/ m^2 h % RH)

RH = Relative Humidity (%)

X = Thickness of wood (cm.)

and:

$$\frac{\delta MC}{\delta t} = Dx \frac{\delta^2 MC}{\delta x^2} + Dy \frac{\delta^2 MC}{\delta y^2} \qquad \text{...(Eq.19)}$$

where:

MC = Wood moisture content (%)

t = Time (h)

x,y = Thickness of wood along its respective axes (radial and tangential)

D_x, D_y = Proportionality coefficients (m^2/h)

The transport coefficient K_h introduced in Equation 18 is called moisture conductivity (Rice 1985), and it can be experimentally determined using the same technique (diffusion cups) described by Siau (1984) to determine diffusion coefficients by the steady-state method. It should be noted that the coefficient of overall moisture transport (D_m) is equivalent to the proportionality coefficients introduced in Equation 19.

According to Siau (1984), the effective transport coefficient (K_m) can be related to the coefficient of overall moisture transport (D_m) introduced in Equation 16, by the following relationship:

$$D_m = \frac{100\ Km}{d_w\ G} \qquad \ldots(\text{Eq.}20)$$

where:

G = Specific gravity of wood based on green volume and ovendry weight (dimensionless)

d_w = Density of water (Kg/m^3)

K_m = Effective transport coefficient (Kg/m h %)

D_m = Coefficient of overall moisture transport (m^2/h)

As the basic difference between moisture conductivity (K_h) and effective transport coefficient (K_m) is with respect to the units in which these two transport coefficients are expressed, Rice (1985) suggested the following relationship to relate K_h and K_m:

$$K_h = K_m \frac{dMC}{dRH} \qquad \text{...(Eq.21)}$$

where:

MC = Wood moisture content (%)

RH = Relative humidity of air (%)

Combining of Equations 20 and 21 yields:

$$D_m = \frac{100}{d_wG} K_h \frac{dRH}{dMC} \qquad \text{...(Eq.22)}$$

Equation 22 expresses the relationship between the moisture conductivity (K_h) determined experimentally using diffusion cups, and the coefficient of overall moisture transport is utilized in the modified Lewis number equation (Equation 16). Equation 22 can only be used for moisture content below the fiber saturation point (FSP).

The effective moisture transport coefficient (K_m) can be experimentally determined using Equation 18 and replacing $\delta RH/\delta x$ by $\delta MC/\delta x$.

Combination of Equations 7, 8, 10 and 22 results in the following expression that can be used to calculate the Lewis number for wood when the moisture content is above 40%:

$$Le_{wd} = \frac{(1.39 + 0.028mc)(G) + 0.165}{[d_wG(1 + mc)]\left[\frac{C_{wd} + mcCp_w}{(1 + mc)}\right] \frac{100K_m}{d_wG} \frac{dRH}{dMC}}$$

...(Eq.23)

For moisture content above the FSP, the effective moisture transport coefficient (K_m), experimentally determined by the "diffusion cups technique" (Siau 1984), is used and Equation 23 becomes:

$$Le_{wd} = \frac{(1.39 + 0.038mc)(G) + 0.165}{[d_wG(1 + mc)]\left[\frac{C_{wd} + mcCp_w}{(1 + mc)}\right] \frac{100K_m}{d_wG}}$$

...(Eq.23.a)

which expresses the Lewis number for wood at moisture contents above the FSP.

E. Temperature Drop Across the Load Equation (TDAL)

The primary objective of this dissertation is to evaluate a model that can be used for control purposes during high temperature drying of southern yellow pine dimension lumber.

The model should incorporate both theoretical and empirical aspects of heat and mass transport phenomena to develop simplified, yet useful equations to describe the drying process. These should relate physical characteristics such as air temperature, velocity, humidity and as well as particular parameters such as basic density, size, moisture and drying rates of the lumber.

The general approach to the development of the temperature drop across the load (TDAL) equation is the following:

Consider the wood element depicted in Figure 1. Unsaturated heated air approaches the wood surface with a constant and uniform temperature Ta. Energy is transferred from the mixture of air and water-vapor to the wood surface which is initially at a lower and uniform temperature Tw_i. The initial moisture content of the wood is assumed to be uniform within the volume and equal to MC_i.

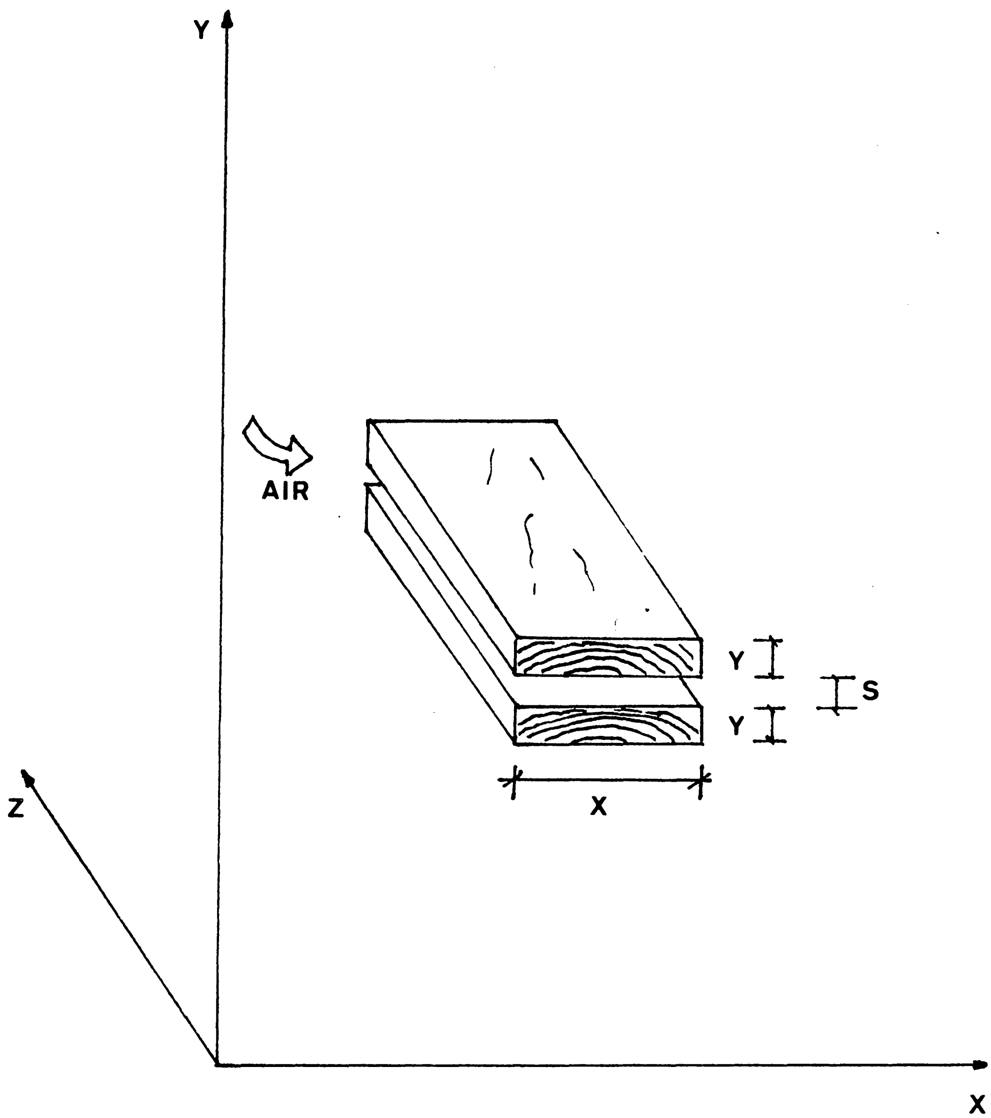

Fig. 1 Schematic representation of a wood volume element in space through which air is flowing.

The energy transferred to the wood element is used to heat the moist wood and to evaporate a certain amount of water. Neglecting small quantities of air inside the wood, an energy balance over the wood element may be written as follows:

$$q(t) = M_{wwd} C_{wwd} \frac{dT}{dt} + L_v d_{wd} \frac{dxdydz}{2} \frac{dMc}{dt} \qquad \ldots (Eq.24)$$

where:

$q(t)$ = Rate of energy reaching the wood (Kcal/h)

M_{wwd} = Mass of wet wood (kg)

d_{wd} = Basic density of wood (Kg/m^3)

x,y,z = Thicknesses of the wood along their axes (cm)

C_{wwd} = Specific heat capacity of wet wood (Kcal/Kg °C)

T = Temperature in the wood (°C)

t = Time (h)

L_v = Latent heat of vaporization of water (Kcal/Kg)

MC = Average wood moisture content (%)

Manipulating Equation 24 (see Appendix 1), the following equation can be obtained:

$$q(t) = d_{wd} (Y/2) Z L_v \frac{dMC}{dt} dx \qquad ...(Eq.25)$$

The rate of energy [q(t)] flowing into the wood can also be expressed by the following equation (Bird et al. 1960) which will be called the "air heat loss equation":

$$q(t) = d_{am} (V/2) Cp_{am} dT \qquad ...(Eq.26)$$

where:

d_{am} = Density of the moist air (Kg/m^3)

V = Air flow rate (m^3/h)

Cp_{am}= Specific heat capacity of the moist air (Kcal/Kg °C

T = Air temperature (°C)

Another equation that can be utilized to calculate the rate of heat flow [q(t)] is the "Newton's Cooling Law" (Bird et al. 1960) usually referred to as the "convective heat transfer equation":

$$q(t) = h (Ta - Ts) Z dx \qquad ...(Eq.27)$$

where:

h = Convective heat transfer coefficient (Kcal/mt^2 h °C)

In a kiln, as the air passes through the lumber pile (Figure 2) , energy is supplied to evaporate water from the lumber. As a consequence, its temperature decreases and relative humidity increases. The intensity of the cooling effect reflects the magnitude of the water evaporated and therefore, the rate of drying.

Mathematically the decrease in the air temperature associated with the evaporation of water from the lumber can be expressed by combining Equations 25 and 26. The resulting equation is termed "temperature drop equation":

$$\frac{dT}{dx} = \frac{d_{wd} \; Y \; Z \; L_v}{d_{am} \; V \; Cp_{am}} \; \frac{dMC}{dt} \qquad \text{...(Eq.28)}$$

The rate of air flow (V) can be expressed by:

$$V = v \; Z \; s \qquad \text{...(Eq.29)}$$

where:

v = Air velocity (Kcal/h)

z = Length of the pile-perpendicular to the air flow (m)

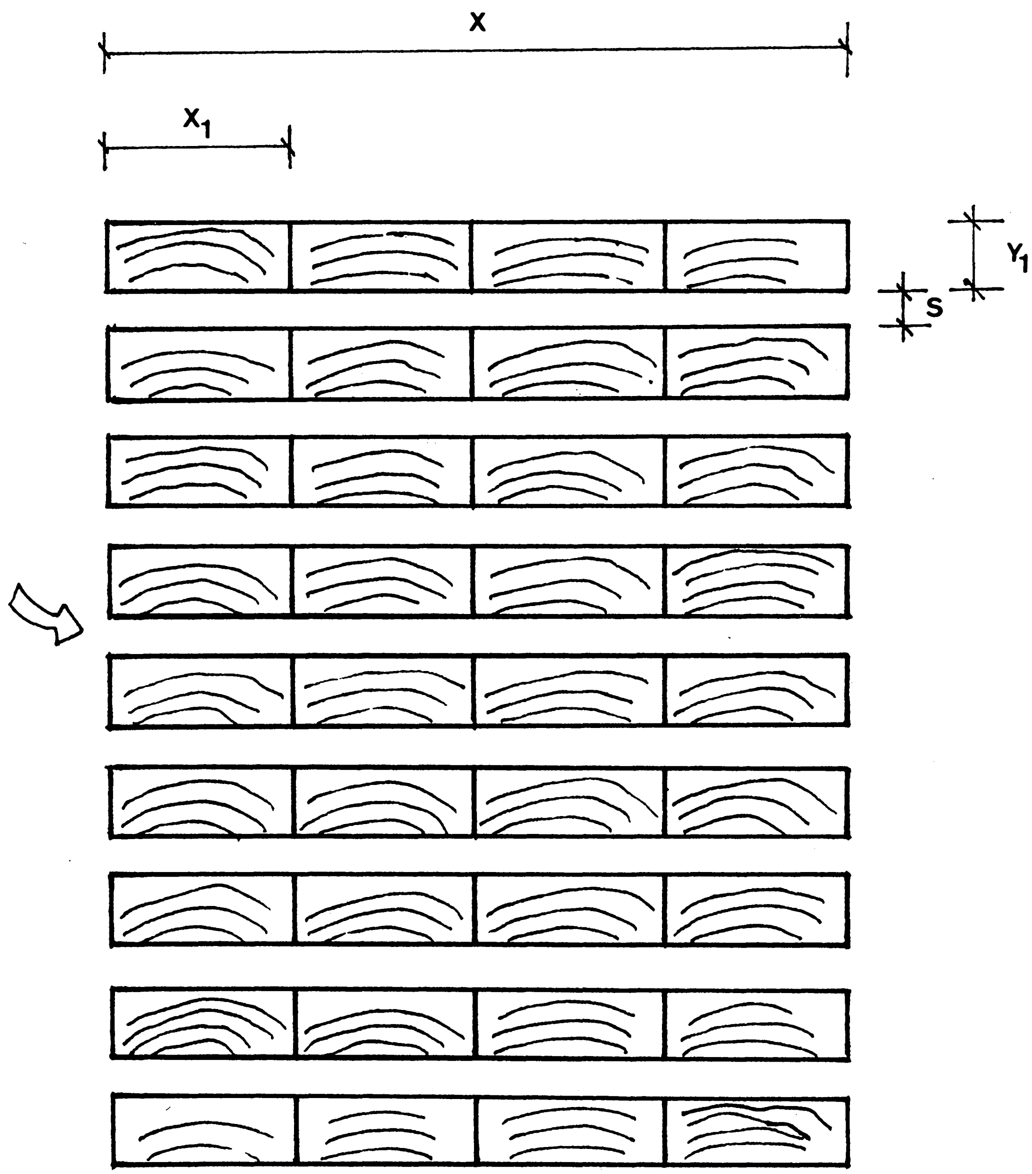

Fig. 2 Lumber pile in a kiln.

s = Distance between 2 layers of lumber [sticker thickness] (cm)

Substituting Equation 29 into Equation 28, assuming constant L_v, physical properties of the air and dMC/dt, yields:

$$\frac{dT}{dx} = \frac{d_{wd}\ Y\ Z\ L_v}{d_{am}\ v\ Z\ s\ Cp_{am}}\ \frac{dMC}{dt} \qquad \text{...(Eq.30)}$$

By integrating Equation 30 across the entire load of width X, the following equation is obtained:

$$TDAL = \frac{d_{wd}\ Y\ Z\ X\ L_v}{d_{am}\ v\ Z\ s\ Cp_{am}}\ \frac{dMC_{avg}}{dt} \qquad \text{...(Eq.31)}$$

MC_{avg} corresponds to the average moisture content of the entire lumber pile.

In some cases, due to the large variation of basic density of wood, it is more convenient to refer to the total mass of water evaporated to express drying rates than to utilize variation in moisture per unit of time. Therefore, the following expression can be written:

$$\frac{dm_{w(avg)}}{dt} = d_{wd}\ Y\ Z\ X\ \frac{dMC_{avg}}{dt} \qquad \text{...(Eq.32)}$$

Substitution of Equation 32 into Equation 31, yields:

$$TDAL = \frac{L_v}{d_{am}\ v\ Z\ s\ Cp_{am}}\ \frac{dM_{w(avg)}}{dt} \qquad \text{...(Eq.33)}$$

and

$$\frac{dm_{w(avg)}}{dt} = \frac{d_{am}\ v\ Z\ s\ Cp_{am}}{L_v}\ TDAL \qquad \text{...(Eq.34)}$$

Equation 34 is the basic model equation for control purposes during high temperature drying of southern yellow pine dimension lumber. If the physical properties of the system wood-drying medium are known, then average drying rates can be evaluated by measuring TDAL.

Combining Equations 25 and 27, the following is obtained:

$$\frac{dMC}{dt} = \frac{h(Ta - Ts)\ Z}{\frac{d_{wd}\ Y\ Z\ L_v\ dx}{2}}\ dx \qquad \text{...(Eq.35)}$$

or

$$\frac{dm_{w(avg)}}{dt} = \frac{h(Ta - Ts)\ Y\ X}{L_v} \qquad \text{...(Eq.36)}$$

Equations 35 and 36 are termed the "drying rate equations". If the convective heat transfer does not change appreciably during the high temperature drying of wood, then drying rate for a particular region of the lumber pile will be a function of the temperature difference between the surface of the wood, and the temperature of the air outside the boundary layer, both temperatures evaluated at a distance x across the lumber pile.

Equations 35 and 36 can also be utilized to predict the convective heat transfer coefficient during the high temperature drying process. Isolating the convective heat transfer coefficient (h) in Equation 36, the following expression is obtained:

$$h = \frac{L_v}{Y\ X\ (Ta - Ts)} \ \frac{dm_{w(avg)}}{dt} \qquad \text{...(Eq.37)}$$

By knowing h, it is possible to rearrange Equation 46 in order to estimate the temperature of the surface of the wood during industrial drying. The following expression is then obtained:

$$Ts = Ta - \frac{L_v}{Y \times h} \frac{dm_{w(avg)}}{dt} \qquad \text{...(Eq.38)}$$

Knowledge of the surface temperature of the wood is extremely important because it could be used to indicate its effects on mechanical properties of the wood. For example Skaar (1976) reported that thermal degradation of dry wood follows a first-order chemical reaction. Thermal degradation increases rapidly with temperature and is ten times greater for wet wood compared to dry wood (Skaar 1976).

Hillis (1984) reports that plasticization of wood occurs at substantially lower temperatures when heating wet wood at temperatures above the boiling point of water. As a result, the wood polymers would form bonds in new positions and consequently, mechanical properties would be affected.

The temperature term, Ta, corresponds to the dry-bulb temperature of the drying medium and the derivation of

Equations 35 and 36 did not take into consideration possible effects due to the humidity conditions of the drying medium. As was cited in a previous section, high mass transfer rates may affect the transport coefficients of momentum, heat and mass transfer (Bird et al. 1960).

CHAPTER SIX

APPROACHES OF THE STUDY

A. Approach to Objective No.1:

-Predicting Drying Rates Through the Temperature Drop Across the Load Equation.

One of the most important short-comings in industrial high temperature drying of southern yellow pine is the lack of the ability to accurately predict or measure the drying rate during the drying process. Due to the severe conditions of temperature, the access to the interior of the kiln is rather limited and therefore conventional sampling of the lumber for periodic moisture content determinations is not feasible. Another operational problem in controlling high temperature drying results because the oven-drying method normally utilized to determine moisture content during drying is too lengthy (usually about 24-hours) compared to the total drying time. Yet, as high temperature drying is a fast process, it is necessary to take rapid control actions in order to avoid irreversible drying quality problems and non-uniform moisture content distribution. Therefore, moisture contents and drying rates must be determined during the process.

To address this problem, this study has as its objective the development of a mathematical model that could be used to estimate drying rates and moisture contents. The equation for the model developed in a previous section is represented by Equation 34:

$$\frac{dm_{w(avg)}}{dt} = \frac{d_{am}\ v\ Z\ s\ Cp_{am}}{L_v}\ TDAL \qquad \ldots(Eq.34)$$

This equation expresses the average drying rate in terms of mass of water removed per unit of time as a function of the physical properties of the air, lumber pile characteristics and the temperature drop across a certain distance in the load. Note that this equation does not require time consuming moisture content determinations. Its simplicity makes it attractive for industrial situations. The terms (physical properties) involved in the equation are: latent heat of vaporization of water, L_v; specific heat capacity, Cp_{am}, and density, d_{am}, of the air and water-vapor mixture; velocity of the air stream, v; width of the lumber pile (length of the air flow path) perpendicular to the direction of the air flow, Z; and the distance between two consecutive layers of lumber (sticker thickness), s. The success of utilizing Equation 34 for controlling industrial high temperature drying will depend on how accurately these physical properties can be estimated during the process. In order to investigate in a laboratory scale the assumptions and simplifications presented in the previous chapter that were used to develop this equation, a small scale drying system was designed to simulate high temperature drying that occurs between two layers of lumber in an industrial kiln. This was done by allowing drying only through the bottom wider face of the upper lumber, and through the top wider face of the lower lumber in the drying layer system. Experiments were conducted at several wet-bulb temperatures to determine the effect of this parameter on drying rates.

With the data collected during all drying experiments, relationships between the average moisture content versus time, surface temperature of the wood versus time, temperature drop across the load versus time, surface temperature versus average moisture content, temperature across the load versus average moisture content, and temperature drop across the load versus the drying rate were obtained. Drying rates were obtained from Equation 34 using measured temperatures. These calculated rates were compared with rates calculated from continuous weight measurements.

The second part of this first objective was to predict the surface temperature of wood during drying. The equation developed to do this is Equation 38 which is:

$$Ts = Ta - \frac{L_v}{Y\ X\ h} \frac{dm_{w(avg)}}{dt} \qquad \text{...(Eq.38)}$$

This equation expresses the surface temperature as a function of several physical parameters, the dry-bulb temperature, and the drying rate. The physical parameters are the latent heat of vaporization of water, L_v; the distance into the pile where the surface temperature is desired, X; the lumber thickness, Y; and the convection coefficient, h. Only the convection coefficient is unknown, so in this experiment it was calculated based on measured temperatures, measured drying rates, and estimated physical parameters.

B. Approach to Objective No.2:

-Relative Magnitudes of Heat and Mass Transfer

Drying of wood is a very complex transport phenomena problem because of the difficulties associated with transport of heat and mass through an inhomogeneous material and a material with physical properties that vary substantially as the moisture content changes. Further, as the wood dries, the moisture content is not uniformly distributed. Likewise, temperature is not uniform. As a result, heat and mass transfer will vary throughout wood and throughout the drying process. The concept expressed by the Lewis Number for the boundary layer was adapted for wood in order to relate magnitudes of heat and mass transfer during the drying process.

The expression for Le_{wd} is:

$$Le_{wd} = \frac{(1.39 + 0.038mc)(G) + 0.165}{[d_wG(1 + mc)]\left[\frac{C_{wd} + mcCp_w}{(1 + mc)}\right]\frac{100K_m}{d_wG}} \quad \ldots(Eq.23.a)$$

All the terms in this equation are easily obtained, physical properties of wood (i.e., in the published literature) except for the effective moisture transport coefficient, k_m. Therefore, an experiment was designed to measure this coefficient at two temperatures below 100 °C. During most of the drying process, the temperature of the wood is not above 100 °C.

CHAPTER SEVEN

DETAILED EXPERIMENTAL PROCEDURES

A. General

Five high temperature drying experiments were performed in order to verify the mathematical equation developed, measure the effect of wet-bulb temperature and determine the convective heat transfer coefficient. An existing laboratory oven was modified to function as a controlled high temperature dry-kiln. The oven also included a system to collect drying data -- temperatures and sample weights -- throughout each experiment without disturbing the drying conditions. The following sections describe the equipment, the control systems and the data collection system.

B. High Temperature Oven

The schematic representation of the high temperature dryer is shown in Figure 3. Internal dimensions were: length = 93 cm, width = 48 cm and height = 64 cm. A centrifugal blower (1/4 HP) recirculated the air in the direction of the length of the dryer. Two vents with manually adjusted baffles allowed the new fresh air to be

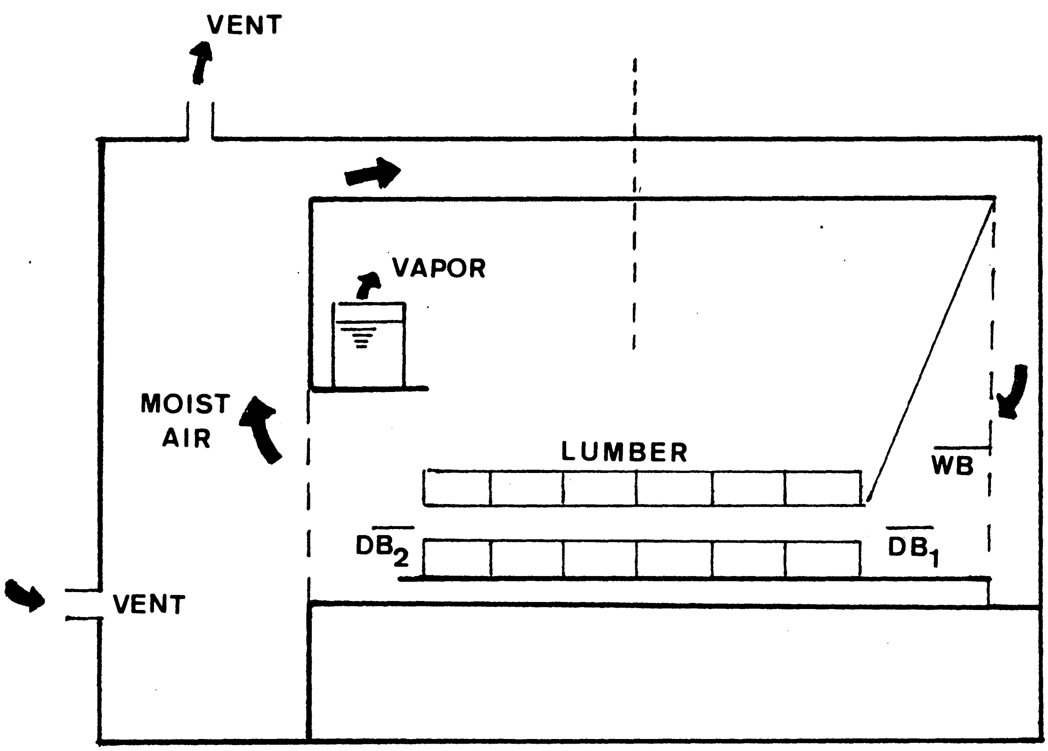

Fig.3 Laboratory oven utilized for the high temperature drying experiments.

brought into the dryer and moist air exhausted. The air was heated by a set of electrical resistance heaters controlled by a thermostat. Air velocity was varied by regulating the internal blower baffle. The maximum air velocity through the load was approximately 375 ft/min (2 m/s). The dryer was placed inside a thermally controlled chamber which maintained a temperature outside of the dryer of approximately 45 °C. This arrangement was necessary to avoid excessive condensation on the dryer walls operating at wet-bulb temperatures above 60 °C. The maximum wet-bulb temperature was approximately 70 °C.

C. Lumber Layer System

As shown in Figure 4, a lumber layer system was designed in order to represent the drying that occurs between two layers of lumber in a lumber pile. A total of 12 samples 17-inches long were utilized in the lumber layer. The air space between the upper and the bottom layer of lumber was 1.0 inch. The total length of the air path was approximately 23 inches (58.4 cm).

The lumber layer system was placed on a rectangular plywood platform which was suspended from its four corners through a cable connected directly to a load beam transducer (Figure 4).

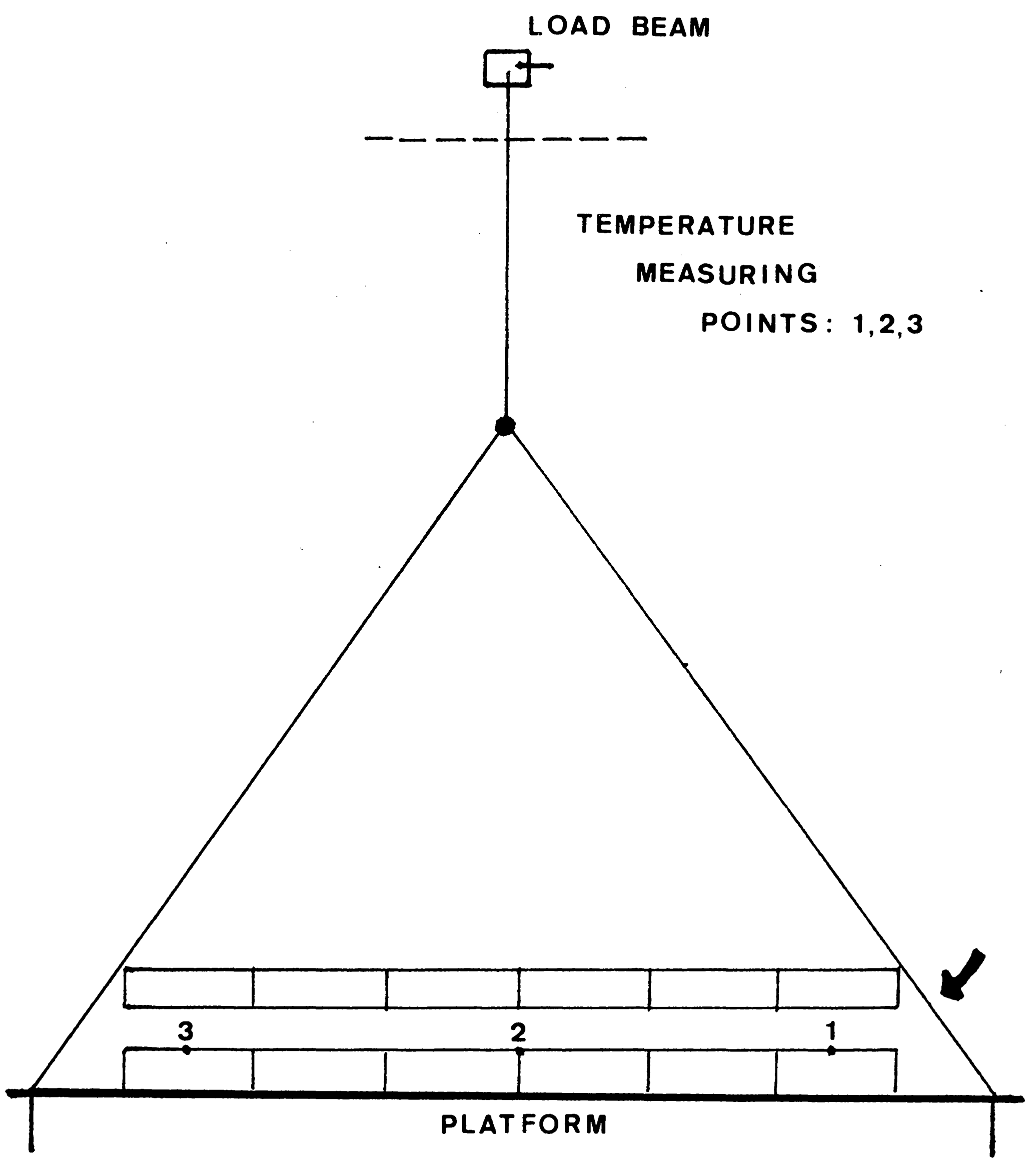

Fig.4 Lumber Layer system utilized.

Four aluminum pins attached to the bottom of the platform near each corner of it, permitted free movement of the platform in a vertical direction while preventing horizontal movement that could affect displacement readings. The plywood platform was entirely sealed with aluminum foil in order to reduce any moisture absorption in the plywood.

D. Load Beam

An alpha type load beam (250 Newtons) manufactured by BHL electronics was utilized to convert vertical platform displacements into voltage readings which in turn were converted into mass of water removed.

Preliminary tests with the load beam (loading and unloading known weights), indicated a calibration constant of 2.05 ± 0.03 mV/Kg for masses ranging between 2,500 Kg and 3,000 Kg (the expected range of total water removal during the drying experiments). A constant excitation voltage of 15.000 V was supplied to the load beam. As illustrated in Figure 3, the load beam was placed outside the experimental dryer and therefore it was not affected by the elevated temperature in the dryer.

E. Temperatures

Figure 3 illustrates the temperature measurements locations. A total of 6 copper-constantan thermocouples (24 AWG), insulated with Teflon measured temperatures. The two dry-bulb temperatures located at each end of the lumber layer system, were positioned in the air stream at approximately 0.5 inches (1.3 cm) from the surface of the lumber.

Surface temperatures of the wood (i.e. 1.6 cm below the surface) were measured by inserting a thermocouple under a splinter near the center of the wide surface of the sample. Surface temperature measurements were taken in the first sample on the bottom lumber layer on the entering air side, in a sample at approximately halfway along the air travel, and in the last board on the exit air side.

The wet-bulb temperature of the incoming air was measured with a thermocouple which was covered with a wick. The wick was kept saturated with distilled water during all experiment. The velocity of the air flowing over the wet-bulb was approximately 1000 ft/min. The wick was visually inspected at every two hours to assure it was well saturated.

F. Humidity Control

The most practical and successful way to maintain the desired humidity inside the dryer was accomplished through the utilization of small vaporizers. The advantage of using such device, is that they produce low heat content vapor (i.e., non-superheated vapor) at relatively fast rates. The vaporizers were located in the upper part of the left side of the dryer (Figure 3). The water-vapor produced was mixed with air currents and the resulting mixture was circulated through the lumber pile. According to a preset-set wet-bulb temperature value, both vaporizers were either turned on or off as needed.

G. Automatic Data Collection and Control System

In order to collect all moisture loss and temperature information, as well as to perform the control of the wet-bulb temperature, a computerized data acquisition and control system was designed. Figure 5 illustrates the interface utilized for data acquisition and control operation. The following devices were incorporated by the system:

1. Hewlett-Packard 41 CV calculator.
2. Hewlett-Packard 3421A control unit.

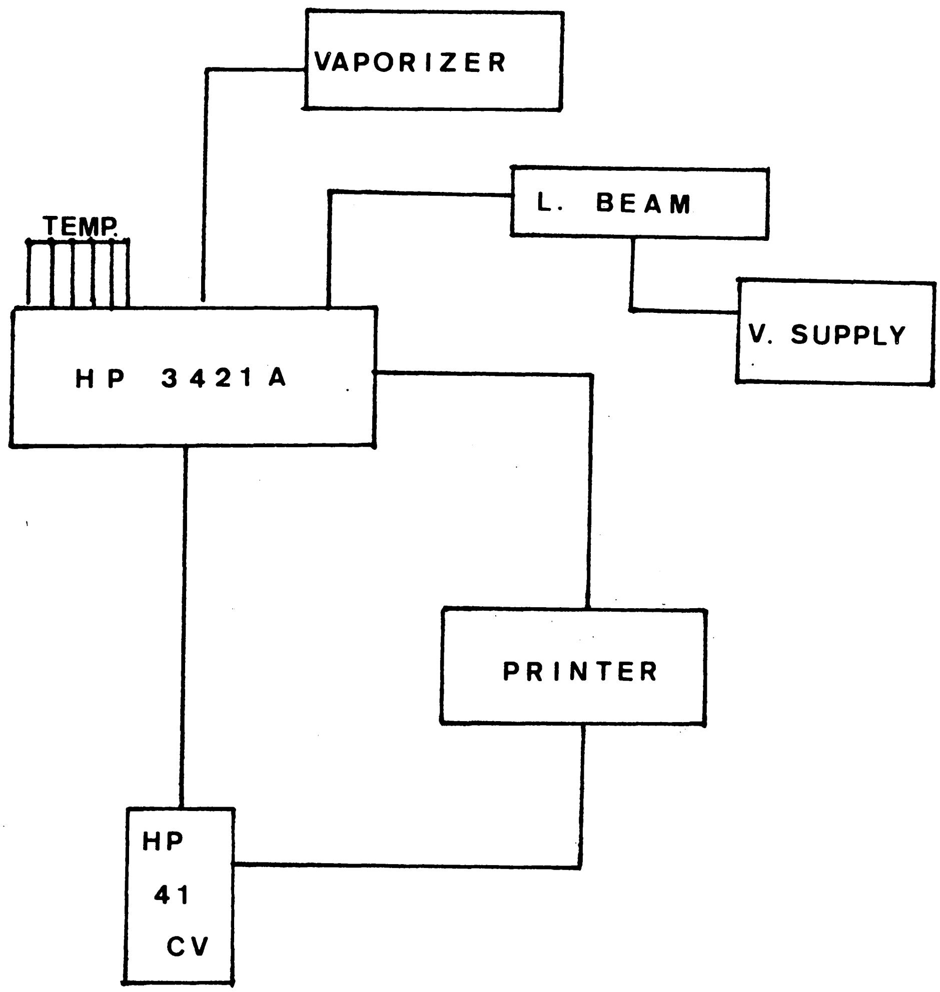

Fig.5 Schematic representation of the data acquisition system.

3. Hewllet-Packard interface loop.
4. A dot matrix printer.
5. An on/off switch relay.
6. Two vaporizers (110 V)
7. Alpha load beam (250 N).

A computer program written for the HP-41 CV (Appendix 3) was designed to automatically collect drying data and simultaneously perform the controlling tasks. Voltage signals received by the HP-3421A control unit were transferred to the HP-41 CV for either further calculations and printing. The data acquisition system was activated every 6 minutes; the wet-bulb control was activated every 3 minutes.

H. Temperature Drop Across the Load Experiments

- Wood: Freshly sawn green loblolly pine (Pinus taeda L.) was utilized in all drying experiments. Two trees were cut into logs, with length ranging from 10 feet (3 m) to 11 feet (3.4 m).

Lumber samples were sawn from the logs with the following nominal dimensions:

thickness = 2 inches (5.1 cm)
width = 4 inches (10.2 cm)
length = 10 feet (3 m)

Immediately after sawing the lumber a visual selection was made to include only flat sawn lumber with no more than one or two small knots.

Samples measuring 2 x 4 x 17 -inches (5.1 x 10.2 x 43.2 cm) (nominal dimensions) were then sawn from the lumber. Each of these samples was then resawn in half along the thickness. Finally, the samples were trimmed to the following dimensions:

thickness = 1 ± 1/16 inches (2.54 ± 0.2 cm)

width = 3-3/4 ± 1/16 inches (9.5 ± 0.2 cm)

length = 17 ± 1/8 inches (43.2 ± 0.2 cm)

- Drying Experiments: Prior to drying, all samples were weighed 0.1 g. Before mounting the sample on the rectangular platform, aluminum foil was applied to all surfaces of the lumber except on the one face where unidirectional drying was intended (wider surface).

Before mounting the samples on the platform, the 3 thermocouples utilized to measure surface temperatures were placed in 3 samples that would be located in the lower layer of the lumber pile. As it was stated earlier, the thermocouples were inserted under a splinter on the wider surface in order to reach a depth of approximately 1/16 inches (1.6 mm). The major difficulty found during this step, was to assure that all thermocouples were inserted at the same position in the wood.

As the drying experiments was terminated, (there was no final moisture content target in any of the performed experiments. Rather the experiment was terminated when the temperature drop across the load was approximately less 3 °C.) all samples were immediately weighed (to 0.1 g) and placed in an oven at a temperature of 103 to 105°C for final moisture content determinations.

I. Determination of the Lewis Number for Wood

Determination of the Lewis number for wood required the calculation of the bulk moisture diffusivity and thermal conductivity. To measure diffusivity four flatsawn loblolly pine samples with thickness of 0.1638 ± 0.0107 inches (0.4 ± 0.03 cm) and approximately 3 inches (7.6 cm) in diameter were prepared in order to be utilized for moisture flux determinations through a Thwing-Albert "vapormeter" diffusion cup (Figure 6). Prior to flux determinations the samples were submerged in a dessicator partially filled with water and a vacuum was drawn so that samples were thereby fully saturated. The vacuum was released after 4 hours. All samples

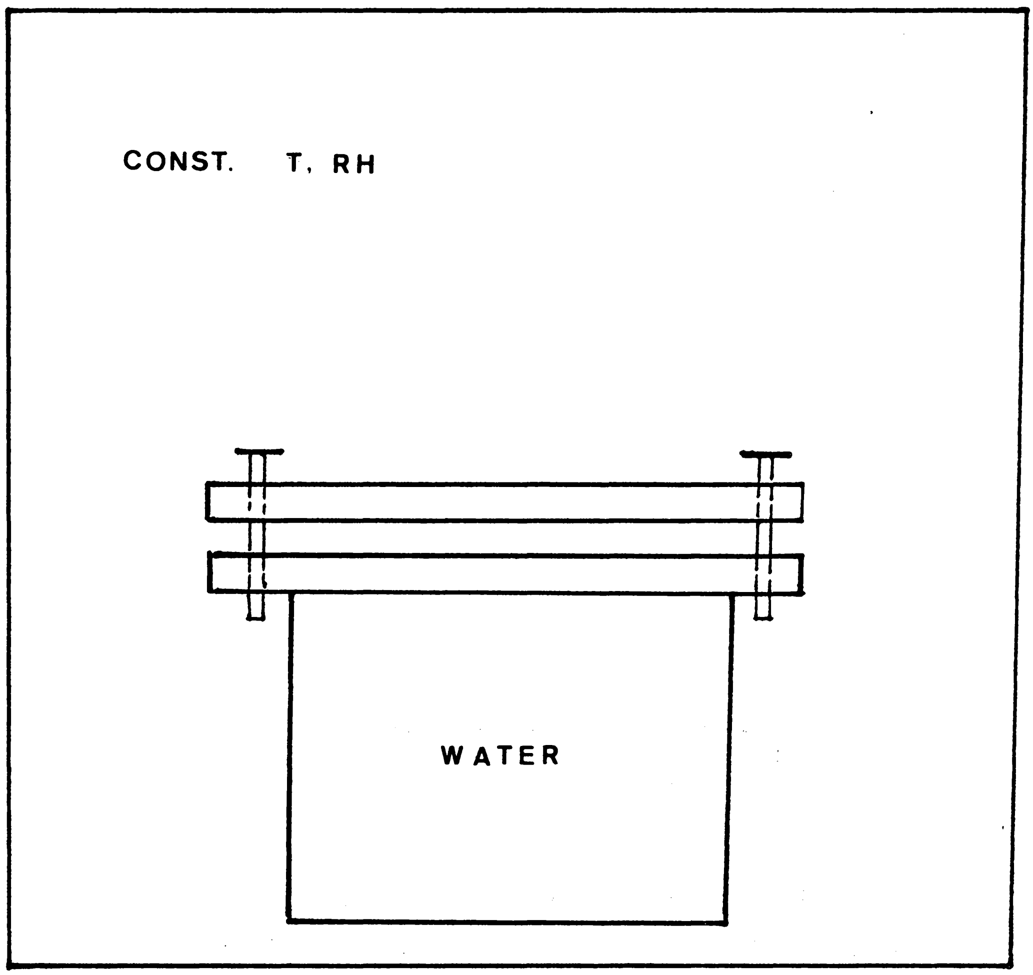

Fig.6 Vapormeter utilized for moisture flux determinations.

remained submerged overnight.

The samples were then weighed to within 0.01 g and mounted in 4 diffusion cups. The diffusion cups were almost completely filled with water and sealed so that the moisture loss would occur only through the exposed area of the wood samples. The total sample exposed area in each cup was 31.669 cm^2.

The assembled diffusion cups were weighed to within 0.01 g and then placed in a laboratory oven in an inverted position in order to assure a constant supply of liquid water on the internal sample surface. The first test was performed at a temperature of 40°C ± 1°C and relative humidity of 35% ± 5%. The second test was at 60°C ± 1°C and a relative humidity of 24% ± 5%. The duration for both tests was approximately 12 hours.

The Lewis number for wood was calculated (Equation 16) correcting the terms, [(moisture conductivity (K_{wwd}), density (d_{wwd}) and specific heat capacity (Cp_{wwd})] for average moisture content of the wood.

CHAPTER EIGHT

RESULTS AND DISCUSSION.

A. Lewis Number

Determination of the Lewis Number for wood (Le_{wd}) requires the overall moisture transport coefficient, thermal conductivity and heat capacity. Two experiments utilizing the vapormeter cup to measure the effective moisture transport coefficient (K_m) were performed. Prior to the moisture loss determinations, all samples were saturated with water which resulted in an average moisture content (dry basis) of 202% ± 12% (confidence interval of 95%).

The average value of moisture flux 2.10×10^{-8} Kg/cm^2s at 40 °C. Substituting average moisture flux (F_{avg}) into Equation 18 and using $\delta MC/\delta x$ instead of $\delta RH/\delta x$, yields:

$$K_m = (2.10\times10^{-8}\times0.4161)/(202-7) = 4.5\times10^{-11} \text{ Kg/cm.s } \%(MC)$$

Using Equation 20, the value for the overall moisture transport coefficient is:

$D_m = 100 \times 4.5 \times 10^{-11} / (1000)(0.47)(10^{6}) = 9.6 \times 10^{-6}$ cm^2/s.

Thermal conductivity at a moisture content of 202% is given by:

$k_{wwd} = 0.47(1.39 + 0.038(2.02)) + 0.165$

$= 0.85$ Btu in/ft^2.h.F

$= 2.94 \times 10^{-7}$ Kcal/cm.s.C

According to Equation 10, the specific heat capacity is:

$Cp_{wwd} = ((2.02)(1)+0.324)/(.1+2.02) = 0.776$ Btu/lb. F (.776 Kcal/Kg °C)

Therefore, utilizing Equation 23a, the Lewis number for wood is:

$Le_{wd} = (2.94 \times 10^{-4})(10^{6})/[(1000)(0.47)(1 + 2.02)(0.776)$

$9.6 \times 10^{-6})] \approx 28$

Following the same steps, for wood at 60 °C and 24% relative humidity, the following values were calculated:

$F_{E(avg)} = 3.25\times10^{-8}$ kg/cm^2.s

$K_m = 6.8\times10^{-11}$ Kg/cm.s.%

$D_m = 1.5\times10^{-5}$ cm^2/s

$Le_{wd} \approx 18.$

For both temperatures (40 °C and 60 °C) the Le_{wd} is greater than 1. This indicates that resistance to mass transfer inside the wood is greater than the resistance to heat transfer.

B. High Temperature Drying Experiments

A total of five high temperature drying experiments were performed. In all experiments the dry-bulb temperature was maintained at approximately 115°C; the wet-bulb temperatures were 50.6 °C, 60.5 °C, 63.7 °C, 65.1 °C and 67.9 °C.

Temperature drop across the load (TDAL), weight losses measurements, dry- and wet-bulb temperatures and temperature near the surface of the wood were monitored throughout all drying experiments.

With the data collected in each experiment, it was possible to construct the drying curve for the process. The drying curve (MC% versus time in hours) was based on the average moisture content for the entire load of lumber.

Drying rates during the process were calculated by substituting estimated air and water physical properties values and observed temperature drop across the load into the empirical model developed (Equation 34).

Observed temperature drop across the load values were related to average moisture content (entire load of lumber) and to the temperature near the surface of the wood (approximately 1/16 inches below the surface).

Convective heat transfer coefficients were estimated the average temperature near the surface of the wood (average along the length of the lumber pile).

The drying conditions utilized in all experiments are shown in Table 1.

The results found for each of the five the high temperature drying experiments are reported and discussed individually below.

Table 1. Drying conditions utilized during the temperature drop across the load experiments.

Experiment No.	DBT[1] °C	WBT[1] °C	H[2] (kg water/kg dry air)
1	116.6±0.3	67.9±0.9	0.24
2	116.8±0.3	65.1±0.4	0.18
3	115.0±0.7	63.7±0.7	0.16
4	115.0±0.6	60.5±0.6	0.13
5	113.3±0.5	50.6±0.3	0.06

DBT = dry-bulb temperature

WBT = wet-bulb temperature

H = absolute humidity

(1) Based on 95% Confidence interval.

(2) Approximate humidity values (Zimmerman and Lavine 1964).

B.1 <u>Experiment No. 1</u>

The drying curve for the process based on the average moisture content for the 12 samples utilized is given in Figure 7. This curve suggests that the drying process consisted of only one continuously decreasing drying rate period. The drying stages suggested by Hann (1964) that characterize drying of wood above 100°C were not discernible. The shape of the curve 7, suggests that either an exponential or a simple linear function could describe the drying curve. The regression equations for these functions were:

$$MC_1 = 118.1e^{-0.17t} \qquad \text{...(R.1)}$$

with a standard error of approximately 2.9%,

and

$$MC_1 = 103.7 - 9.79t \qquad \text{...(R.2)}$$

with $r^2 = 0.99$

Both model equations, based on r^2 values, described the drying curve well. The drying rates described by the exponential model vary from approximately 16.9 %MC/h to 4.3 %MC/h with an average drying rate of about 10.6

%MC/h. The "constant" drying rate obtained from the linear model (≈ 9.8 %MC/h).

Predicted drying rates estimated through Equation 34 are shown in Figure 8 as a function of MC along with the experimentally observed average drying rates based on weights. A discussion of the values of the coefficients in this equation is provided later. Except for the early part of the drying process, above 90% MC, the predicted drying rates are close to the observed values. Below 50% predictions of drying rates were substantially closer to the observed values The temperature drop across the load (TDAL) was related to moisture content (figure 9). The TDAL dropped steeply in the beginning of the drying process (above 80% MC). The linear regression equation for TDAL versus MC was:

$$TDAL_1 = 8.5 + 0.12MC \qquad \text{...(R.3)}$$

with $r^2 = 0.89$

Temperature drop across the load was related to the surface temperature (Figure 10). The linear regression for TDAL versus Ts was:

$TDAL_1 = 50.4 - 0.37Ts$ ...(R.4)

with $r^2 = 0.94$

The dry- and wet-bulb temperatures, the TDAL1 and the surface temperature of the wood (Ts) increased continuously throughout the drying process; it was always above the wet-bulb temperature.

The linear regression for Ts versus MC was:

$Ts_1 = 112.1 - 0.33MC$ ...(R.5)

with $r^2 = 0.95$

The convective heat transfer coefficient (h) was calculated (Equation 37) utilizing observed values of drying rates and surface temperature. The average value throughout the drying process varied within the interval 7.2 - 18.9 Btu / (ft^2 h °F) (35.2 Kcal(/m^2 h °C) - 92.3 Kcal/(m^2 h °C)).

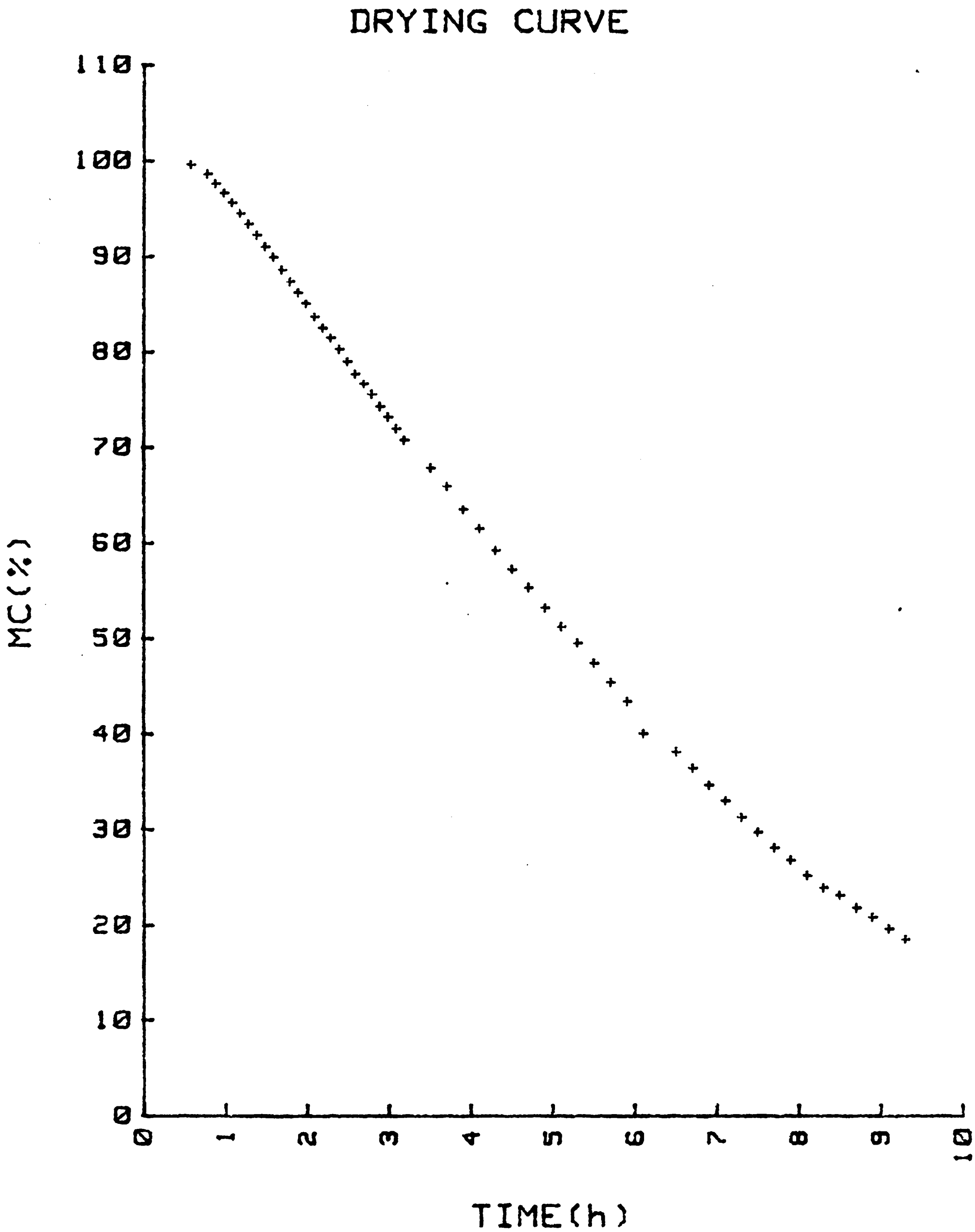

Fig.7 Drying curve, Experiment 1.

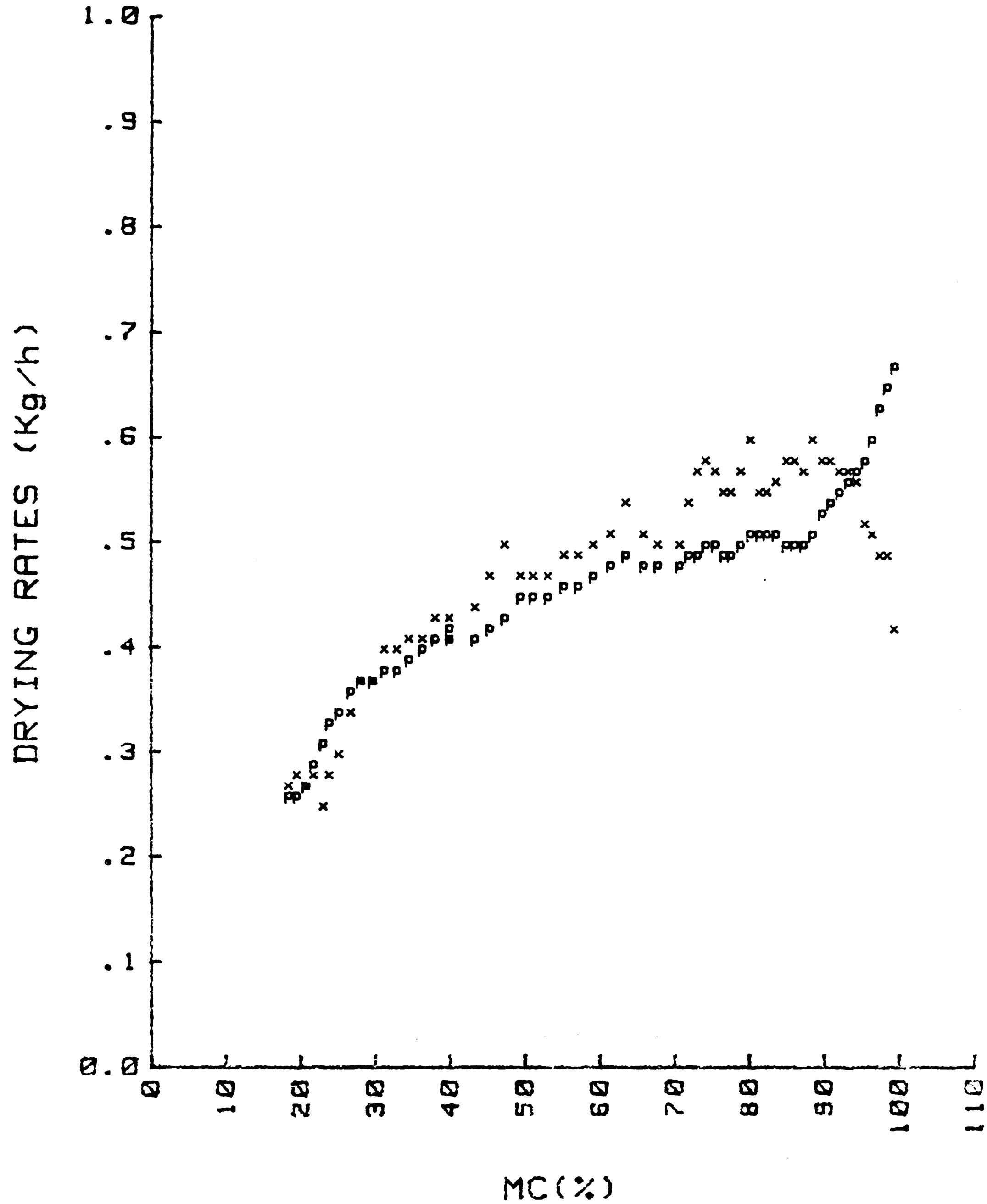

Fig.8 Predicted and observed drying rates (x-observed, p-predicted), Experiment 1.

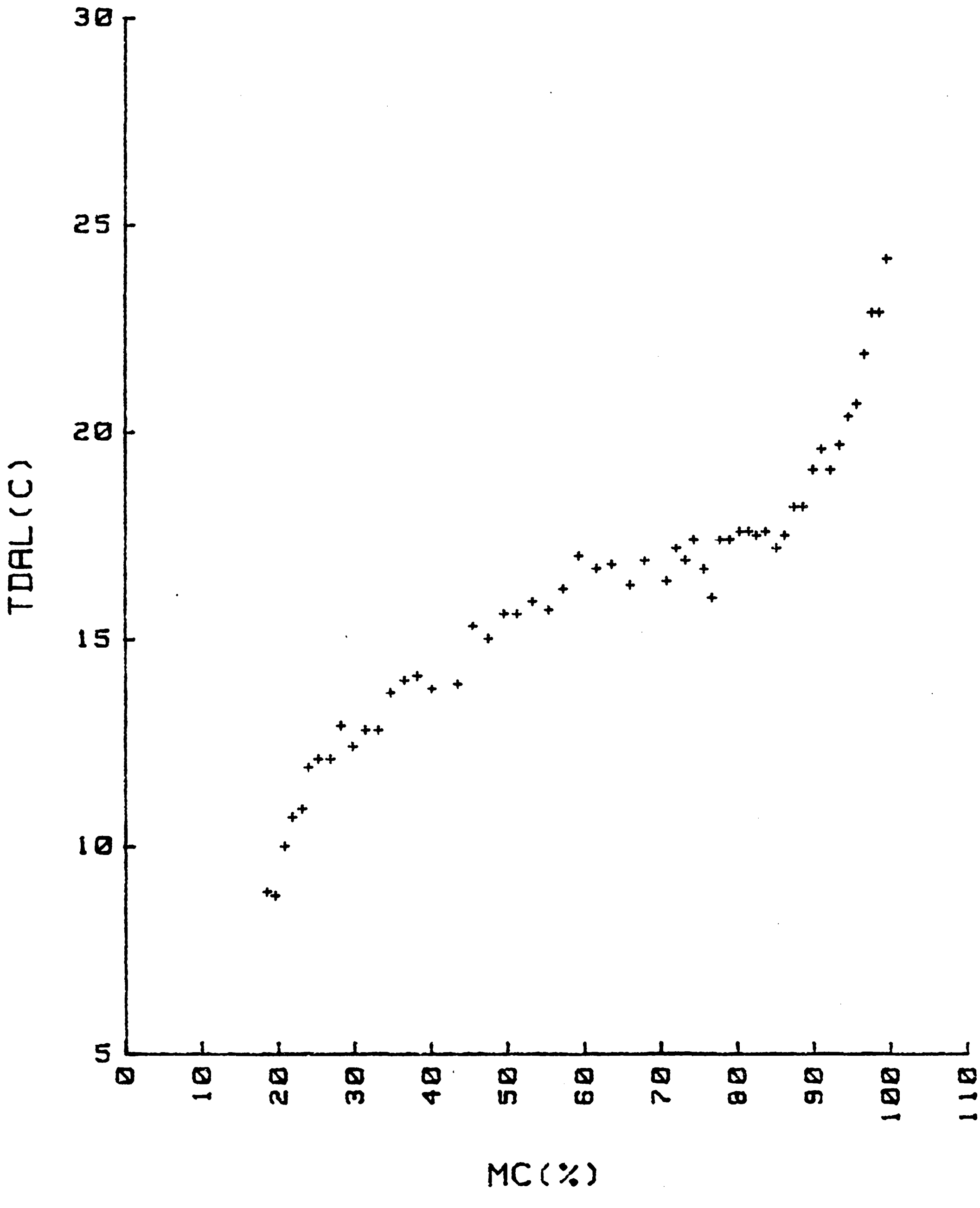

Fig.9 Temperature drop across the load versus moisture content, Experiment 1.

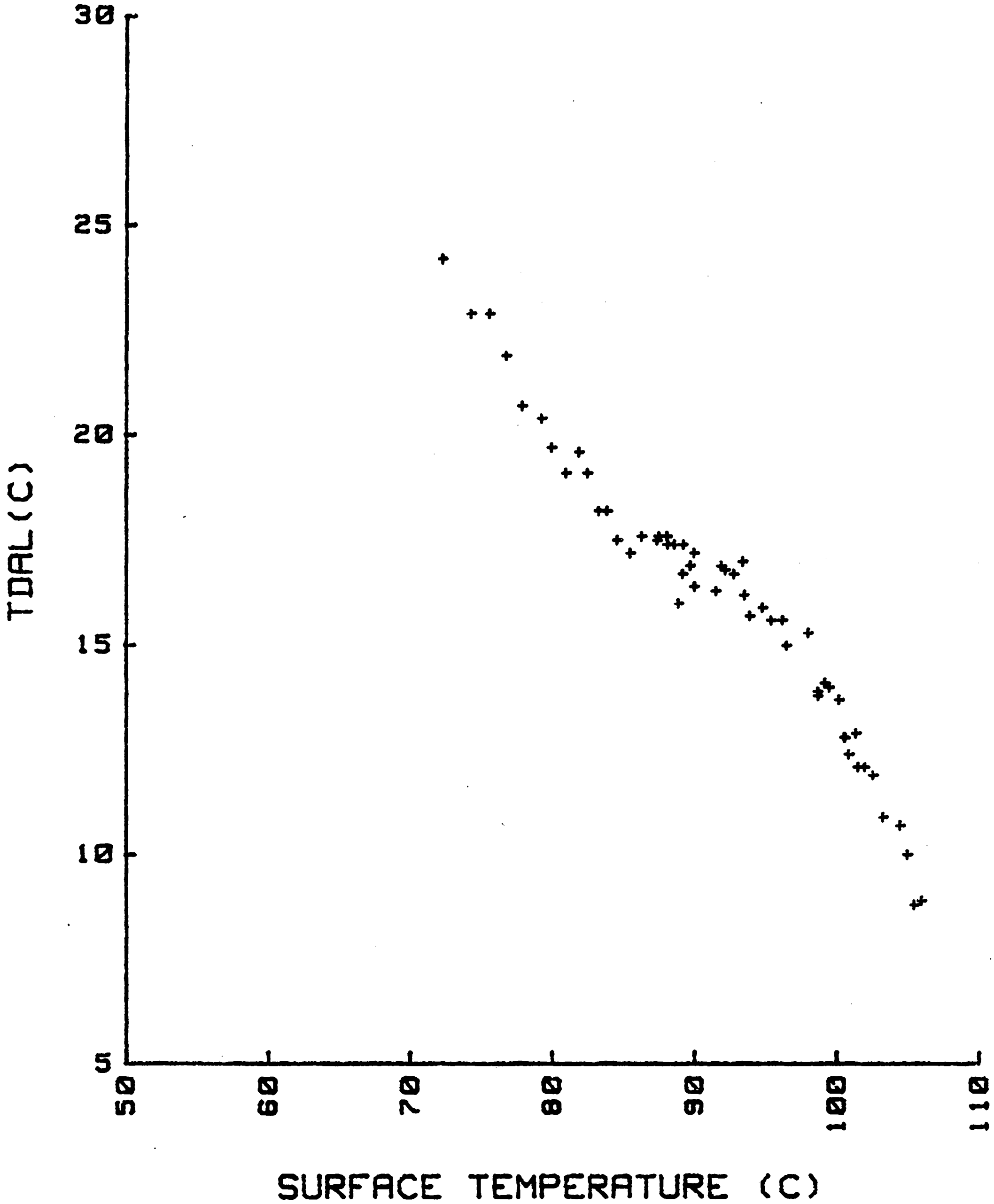

Fig.10 Temperature drop across the load versus temperature near the surface of the wood, Experiment 1.

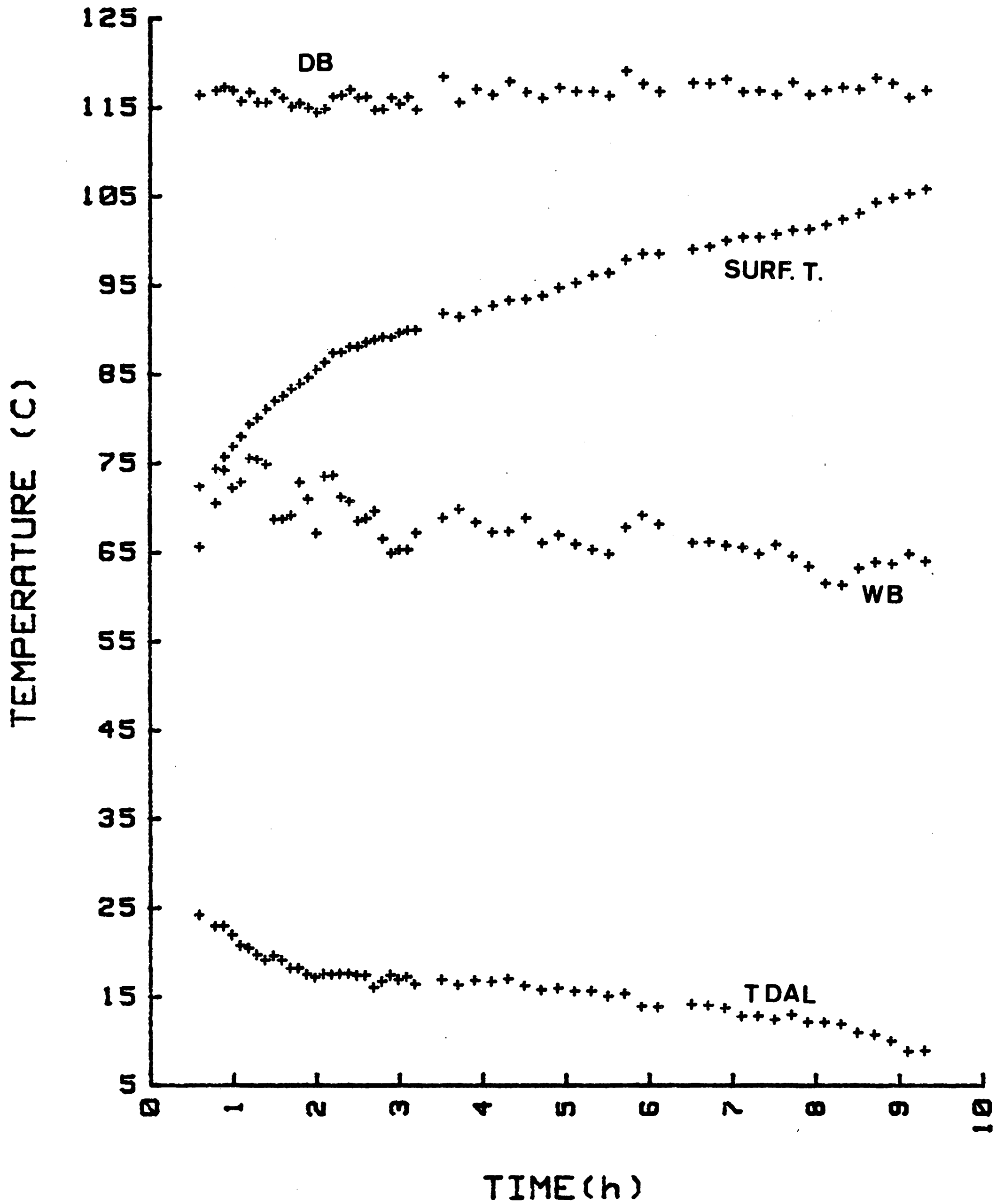

Fig.11 Dry and wet-bulb temperatures, surface temperature and temperature drop across the load, Experiment 1.

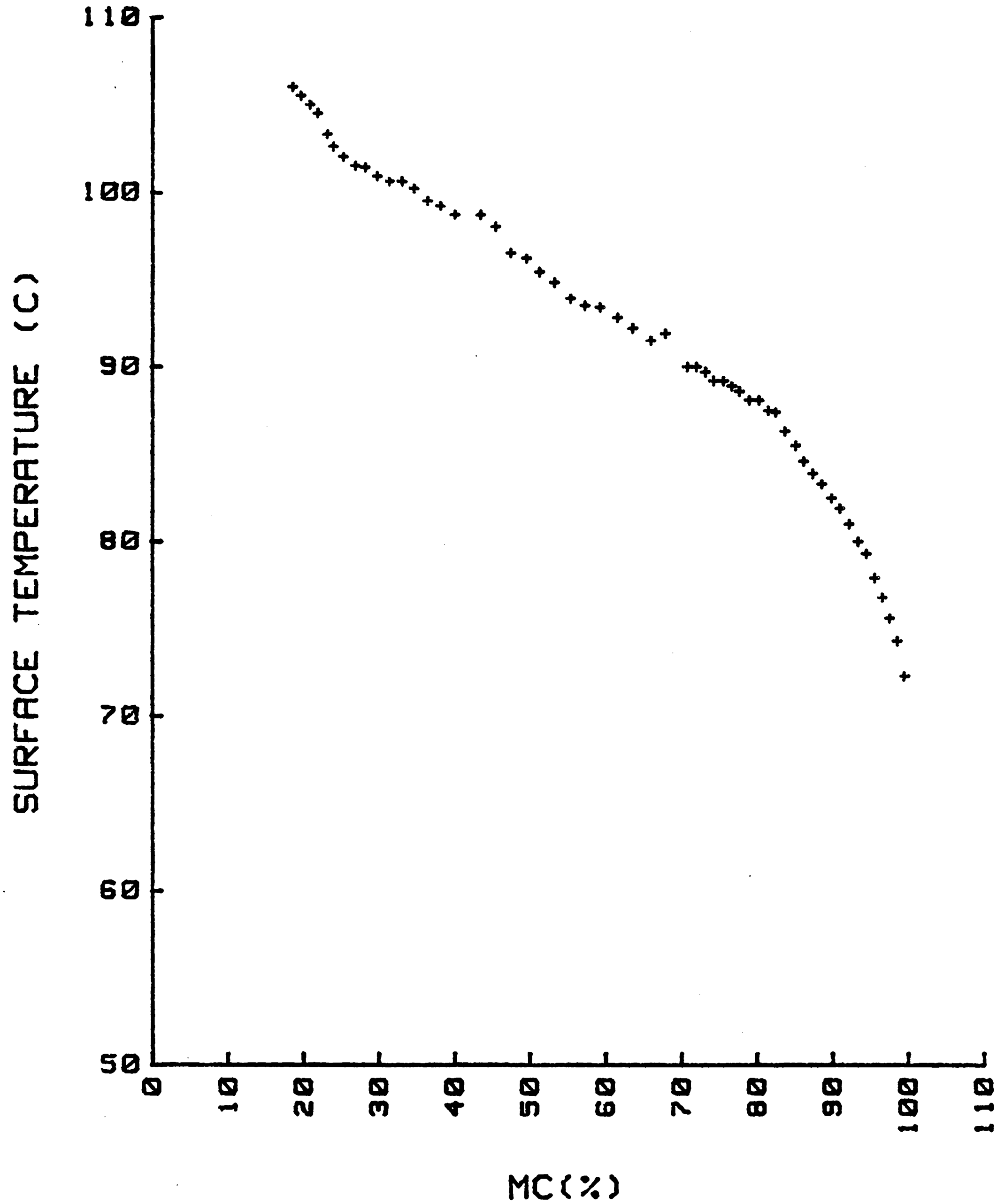

Fig.12 Temperature near the surface of the wood versus moisture content, Experiment 1.

B.2 Experiment No. 2

The results for Experiment No. 2 as well as for the subsequent experiments, will be presented in the same sequence utilized in describing the results of Experiment No. 1. A more detailed discussion of the results will be presented later.

The drying curve for the Experiment No. 2 is shown in Figure 13. The regression equations were:

$MC_{e} = 120.8e^{-0.19t}$ ...(R.6)

with SSR = 3.210%

and

$MC_{e} = 105.1 - 10.4t$ ...(R.7)

with $r^2 = 0.99$

The predicted values were close to the observed drying rates (figure 14).

Figures 15 and 16 present TDAL versus MC and versus Ts. The linear regression equations were:

$TDAL_{e} = 8.8 + 0.21MC$ ...(R.8)

with $r^2 = 0.97$

and

$$TDAL_2 = 75.8 - 0.60\ Ts \qquad ...(R.9)$$

with $r^2 = 0.98$

The linear regression for Ts versus MC (figure 18) was:

$$Ts_2 = 111.8 - 0.35MC \qquad ...(R.10)$$

with $r^2 = 0.97$

The convective heat transfer coefficient ranged from 9.8 to 24.1 Btu/ (ft^2 h °F) (47.8 Kcal/(m^2 h °C) to 117.7 Kcal/(m^2 h °C).

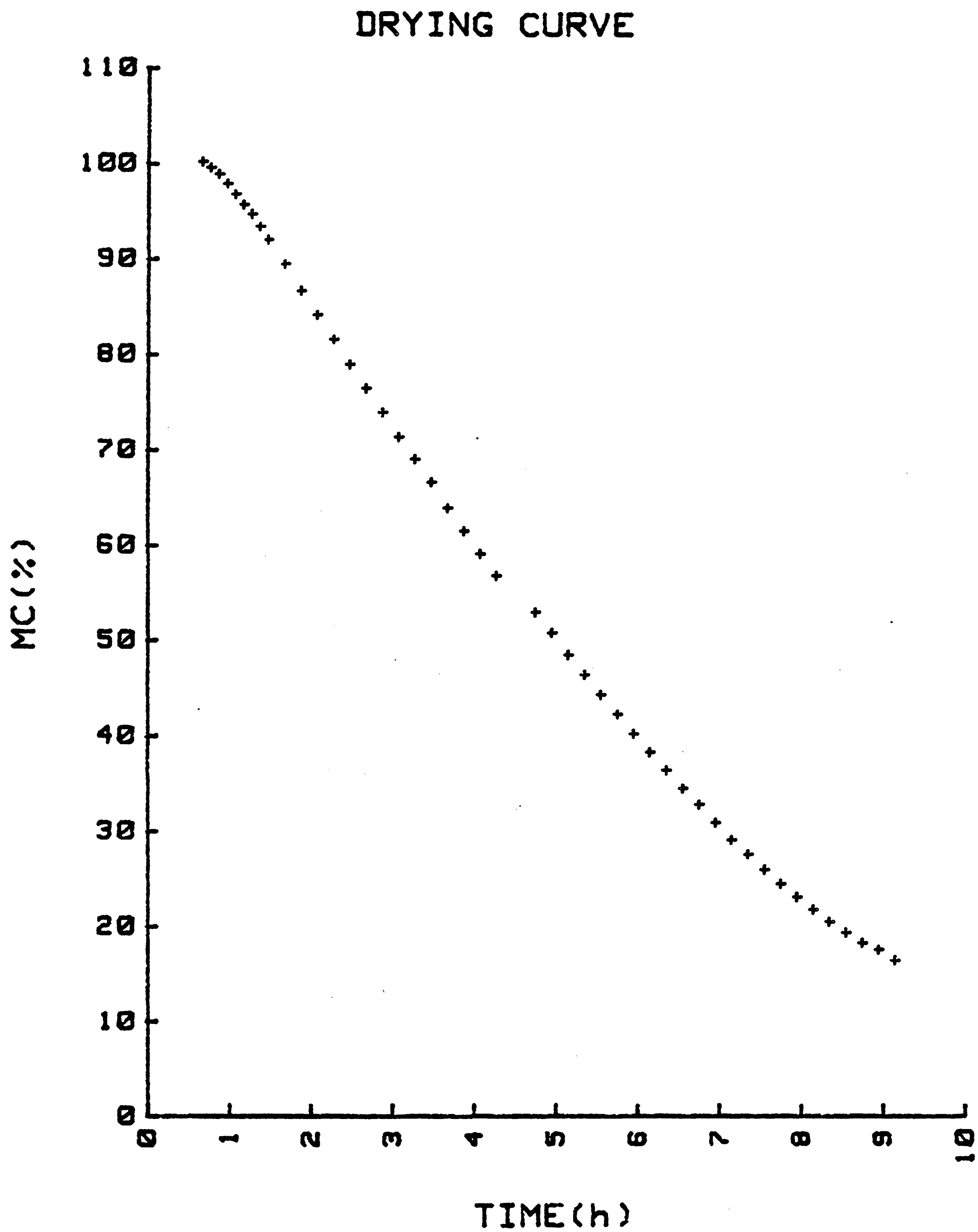

Fig.13 Drying curve, Experiment 2.

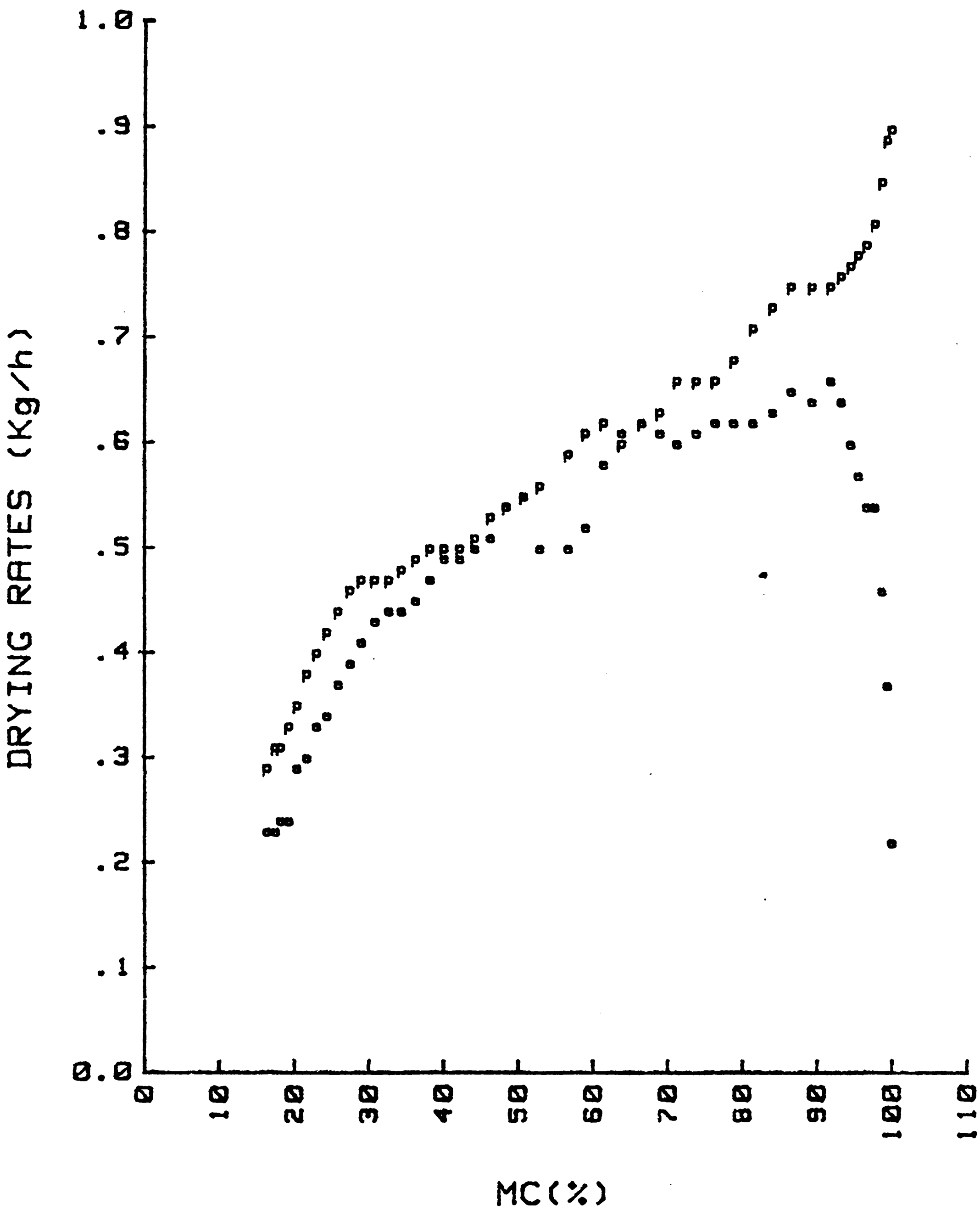

Fig.14 Predicted and observed drying rates

(x-observed, p-predicted), Experiment 2.

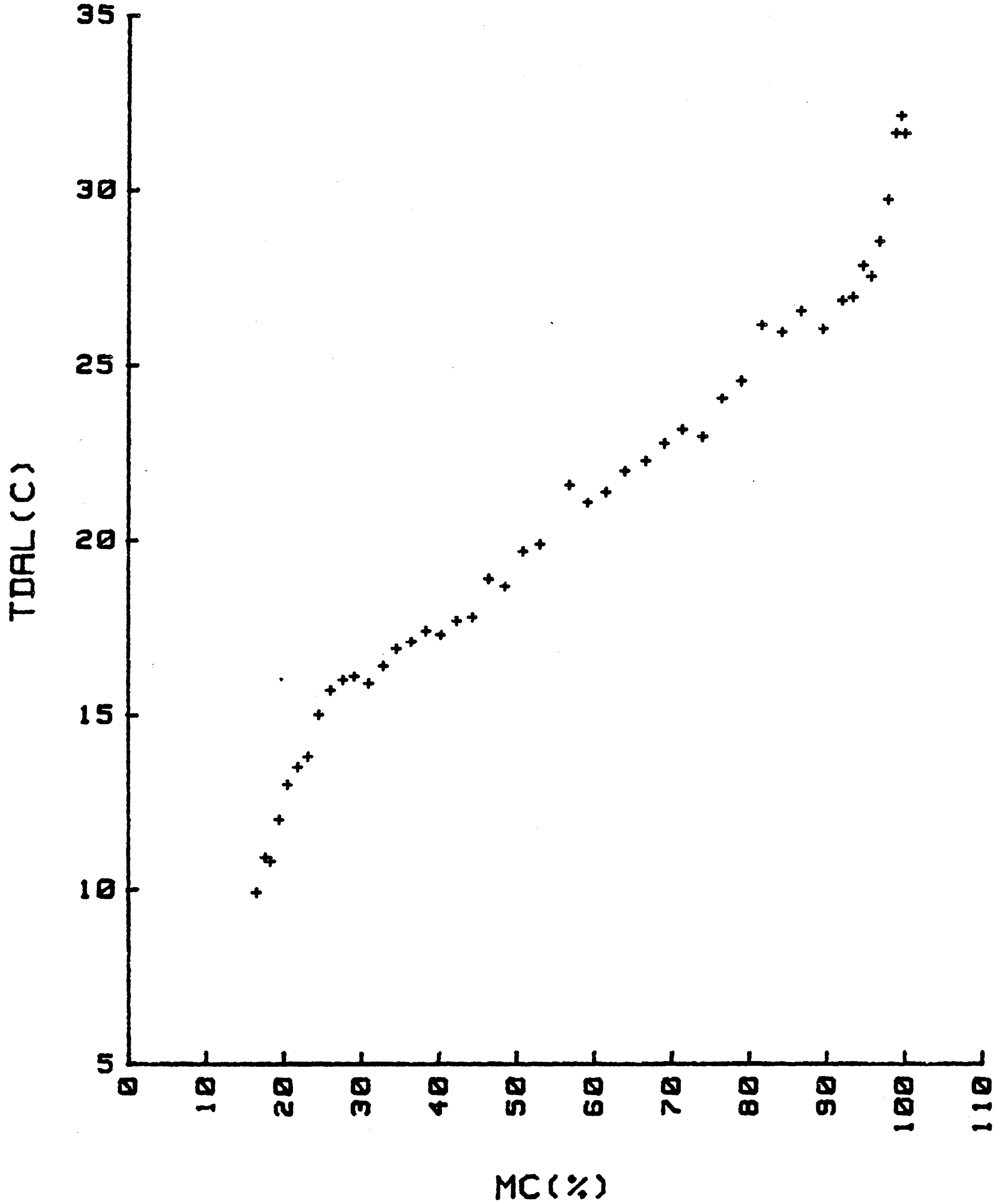

Fig.15 Temperature drop across the load versus moisture content, Experiment 2.

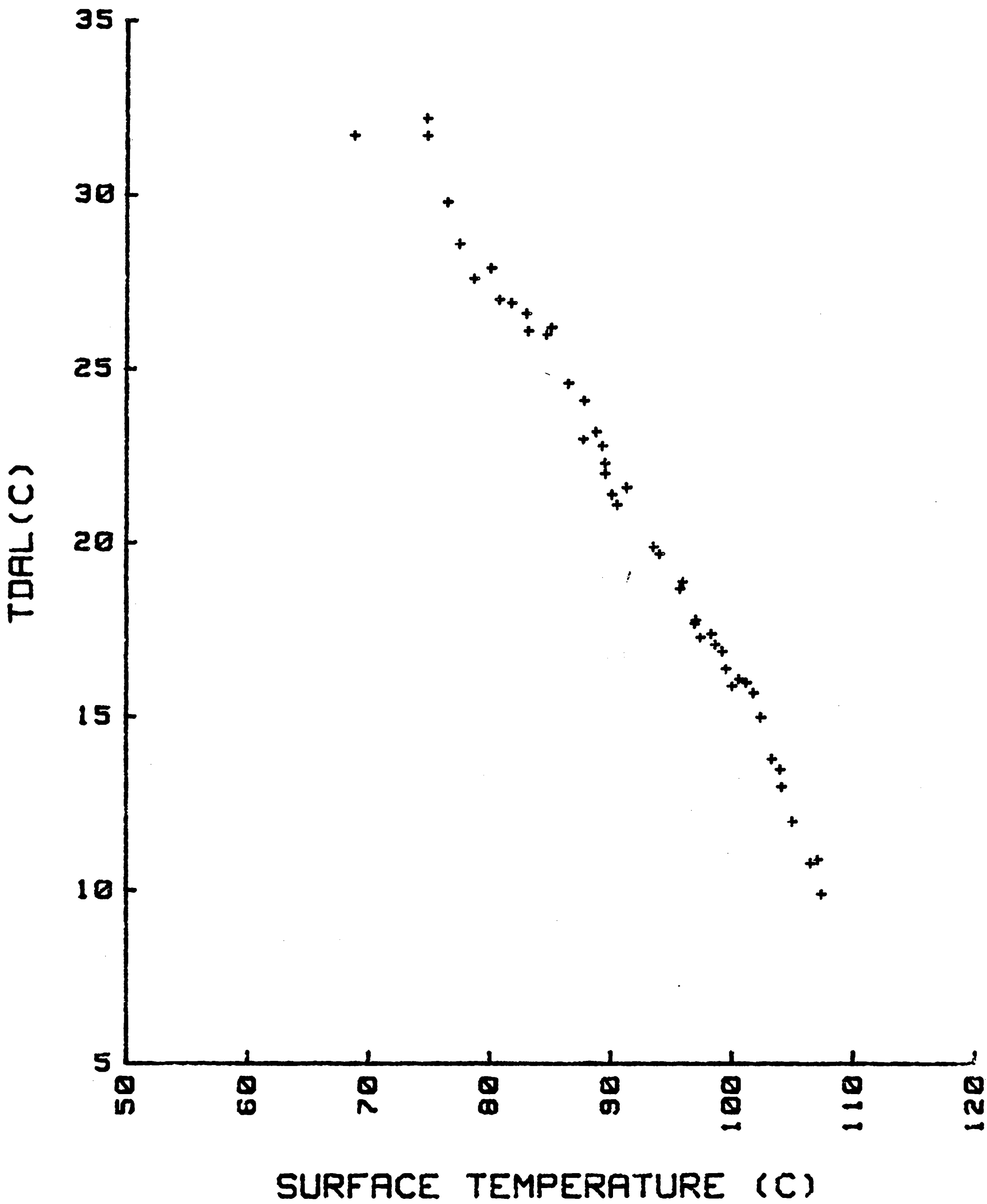

Fig.16 Temperature drop across the load versus temperature near the surface of the wood, Experiment 2.

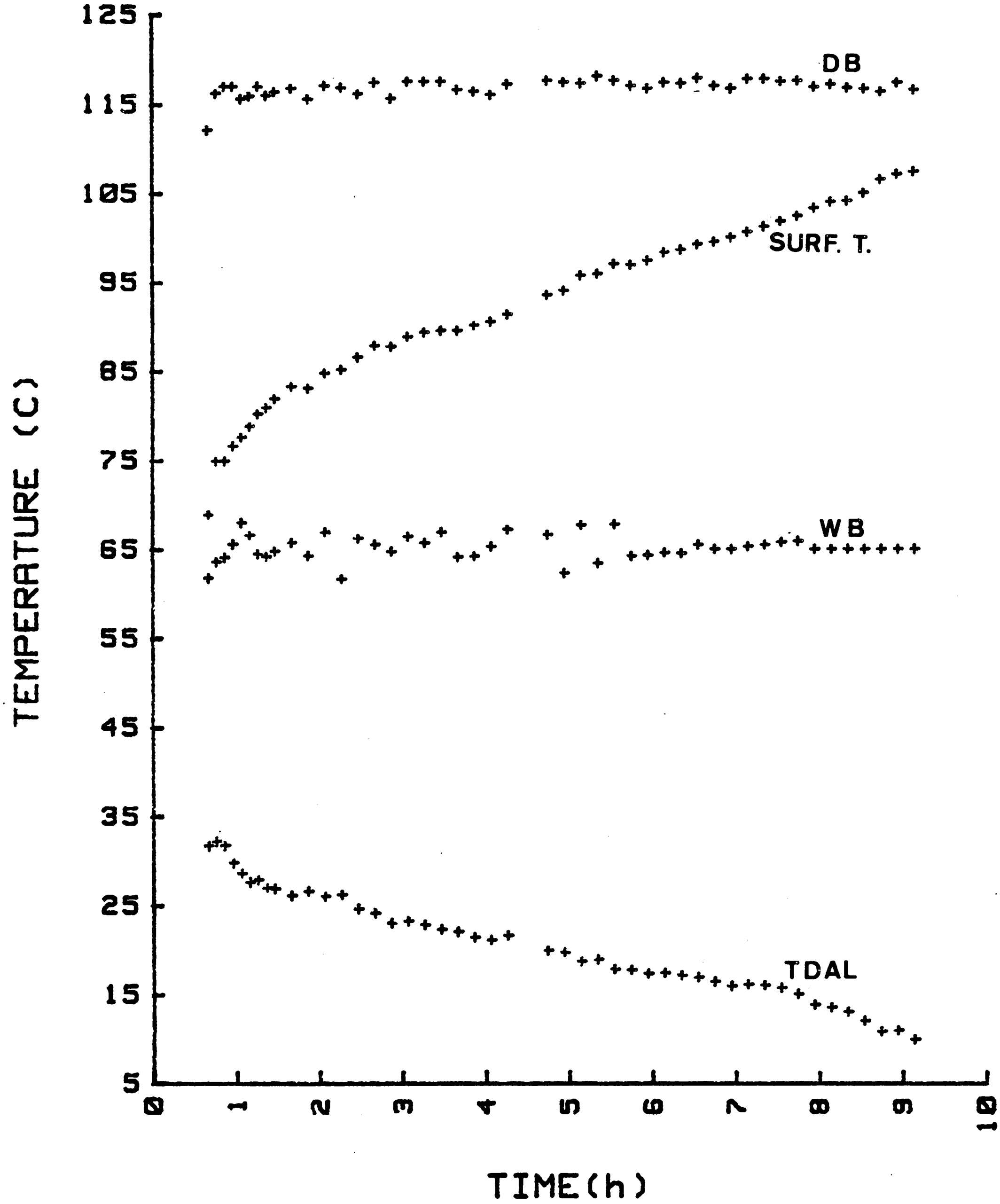

Fig.17 Dry and wet-bulb temperatures, surface temperature and temperature drop across the load, Experiment 2.

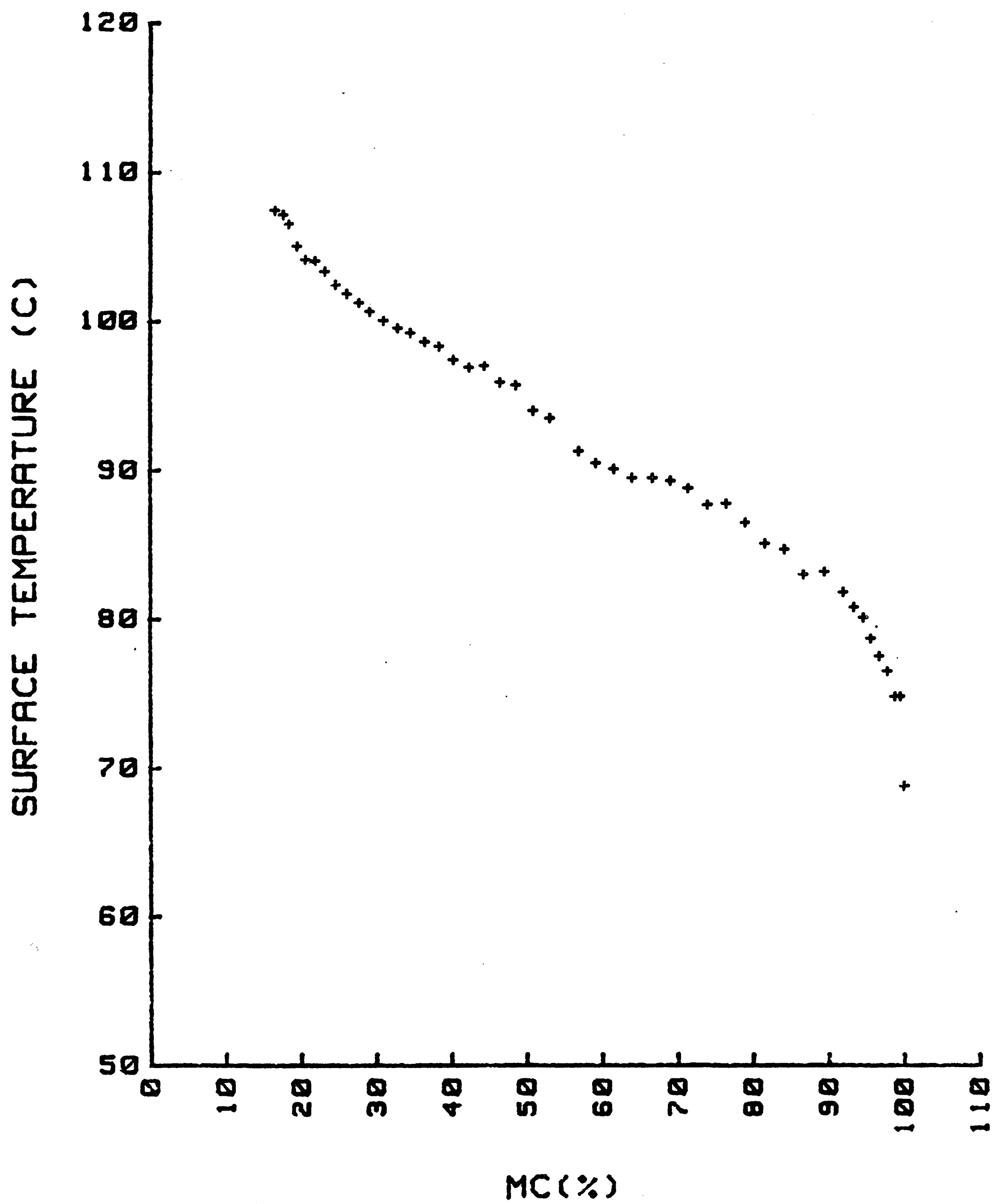

Fig.18 Temperature near the surface of the wood versus moisture content, Experiment 2.

B.3 Experiment No. 3

The drying curve is shown in Figure 19. The regression equations were:

$MC_3 = 81.0e^{-0.22t}$ ...(R.13)

with SSR = 1.960%

and

$MC_3 = 70.7 - 8.02t$ ...(R.14)

with $r^2 = 0.98$

Below 60% MC the predicted values were very close to the actual observed rates (Figure 20).

The linear regression equations relating TDAL to MC and to Ts (Figures 21 and 22 respectively) were:

$TDAL_3 = 2.70 + 0.29MC$ ...(R.15)

with $r^2 = 0.93$

and

$TDAL_3 = 51.2 - 0.42Ts$ ...(R.16)

with $r^2 = 0.96$

The linear regression for Ts versus average moisture content (Figure 24) was:

$$Ts_3 = 114.1 - 0.67MC \qquad \text{...(R.17)}$$

with $r^2 = 0.94$

The estimated average convective heat transfer coefficient ranged from 6.0 to 14.3 Btu / (ft^2 h °F) (29.3 Kcal/(m^2 h °C) to 69.8 Kcal/(m^2 h °C)).

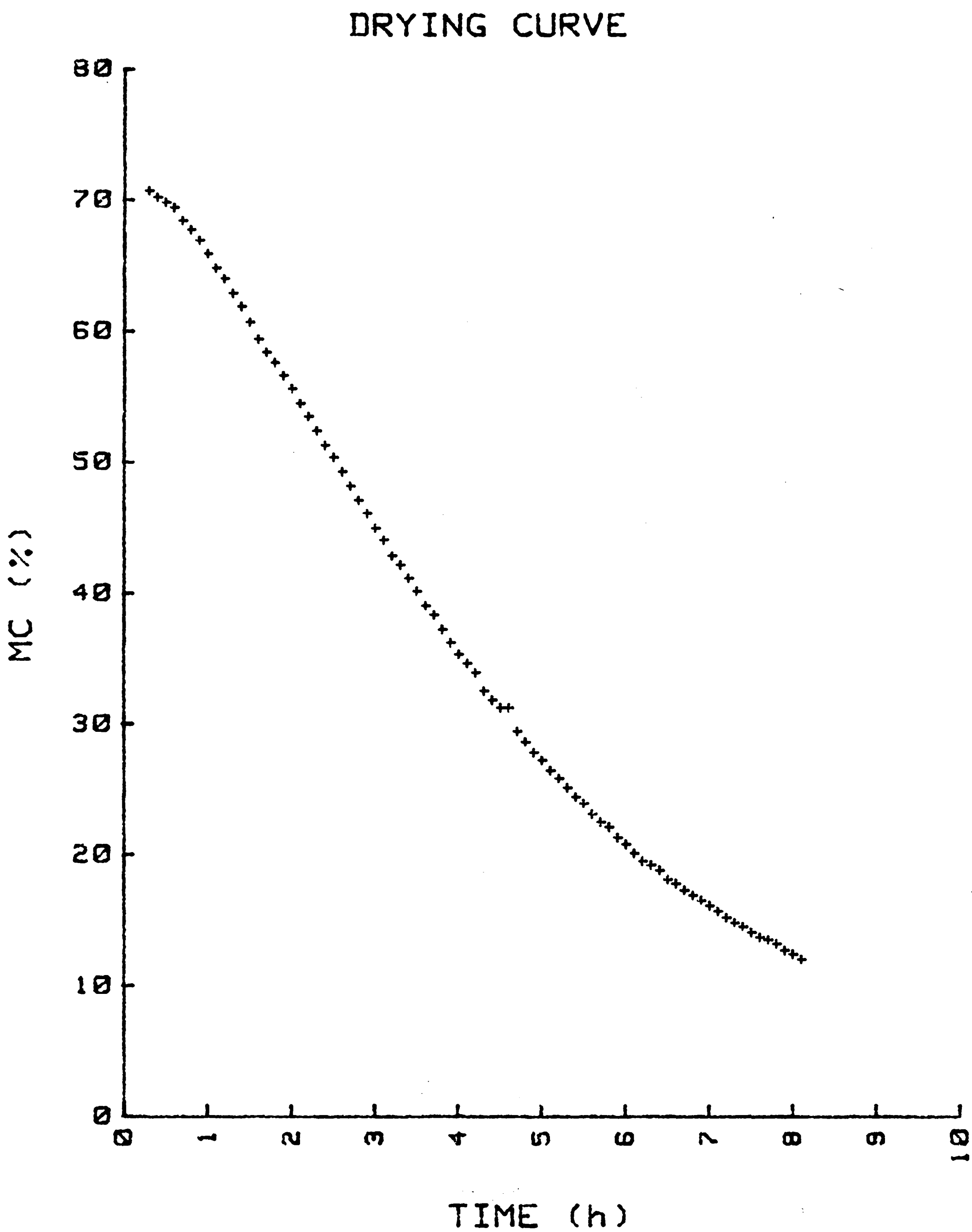

Fig.19 Drying curve, Experiment 3.

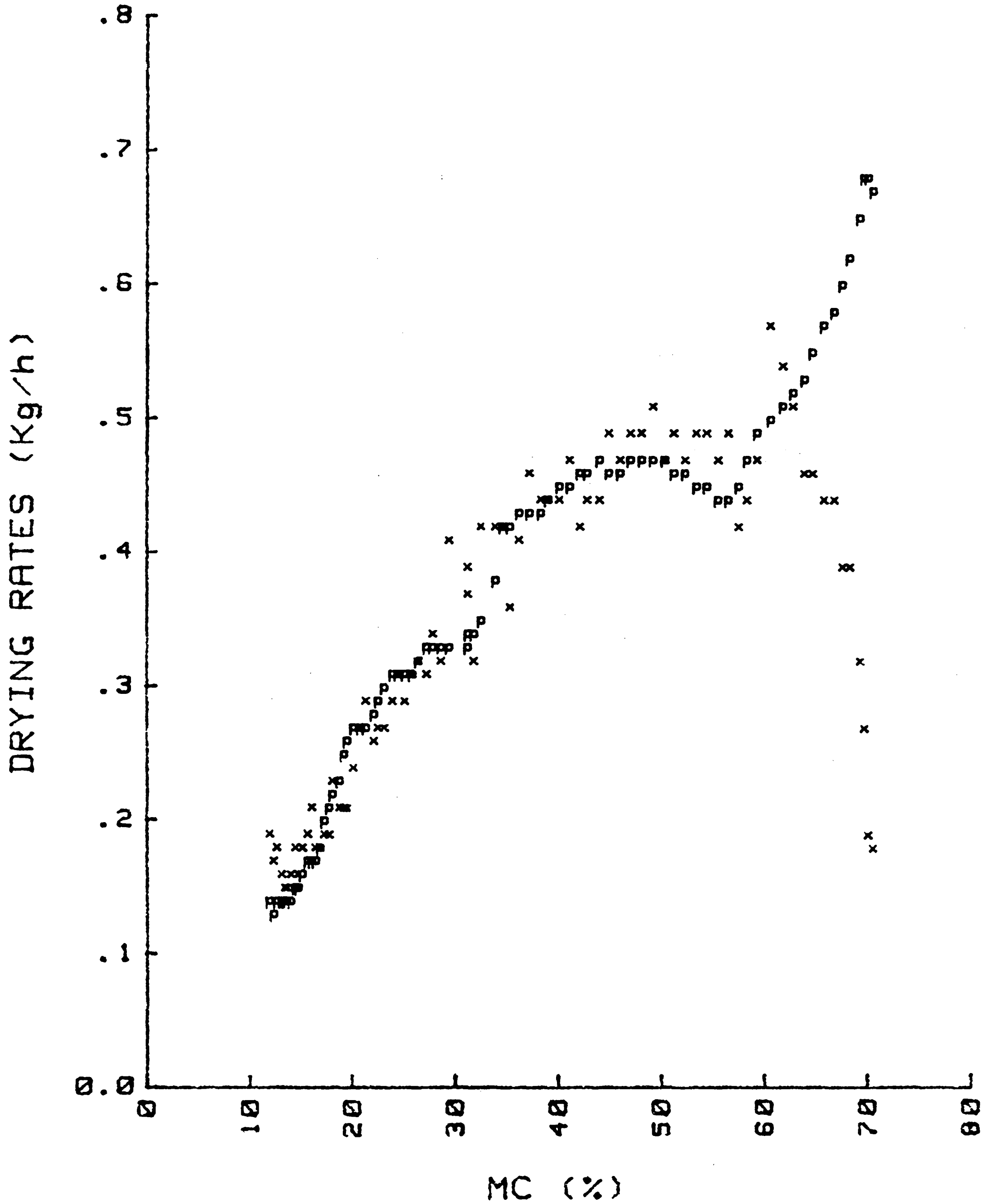

Fig.20 Predicted and observed drying rates

(x-observed, p-predicted), Experiment 3.

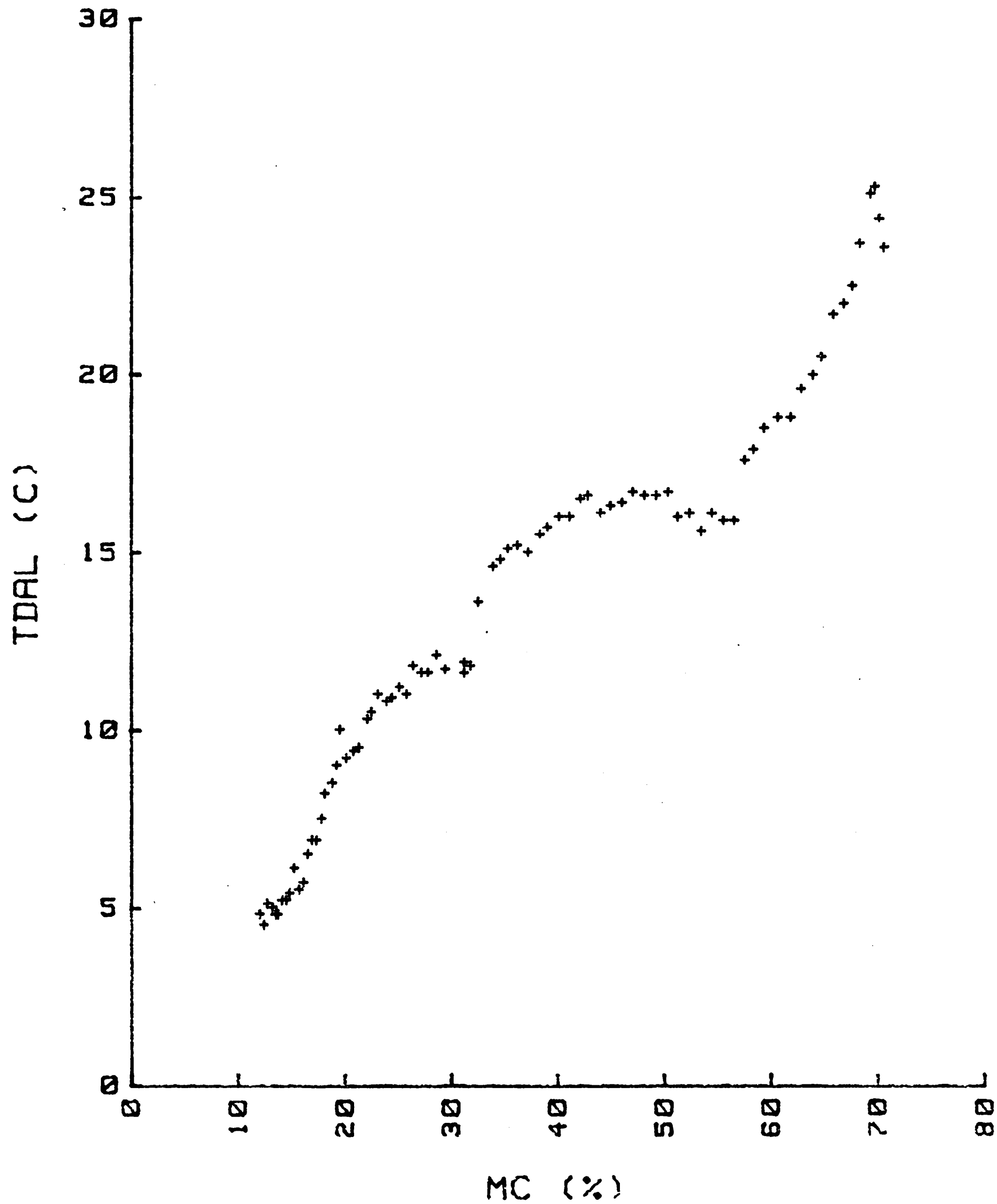

Fig.21 Temperature drop across the load versus moisture content, Experiment 3.

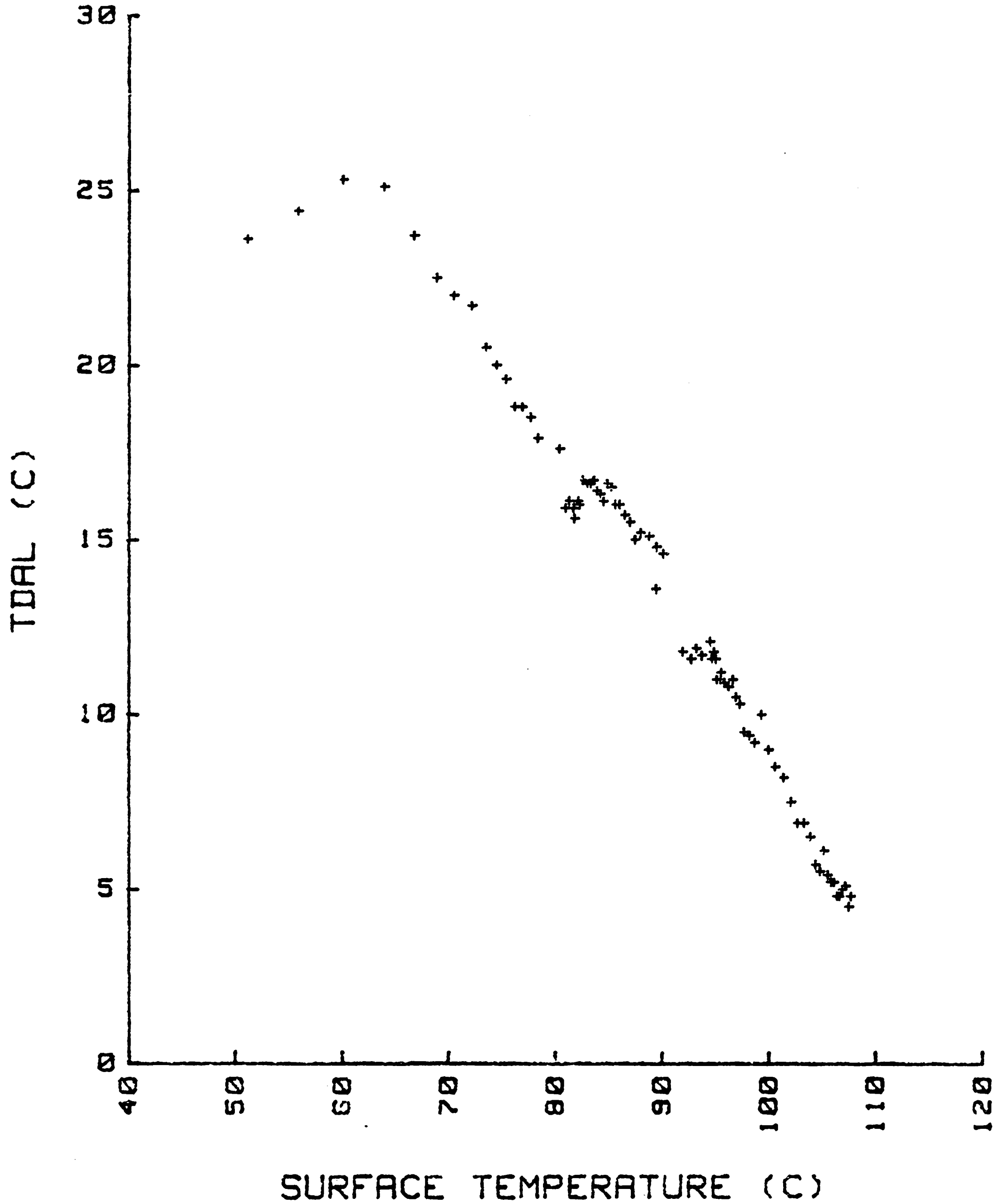

Fig.22 Temperature drop across the load versus temperature near the surface of the wood, Experiment 3.

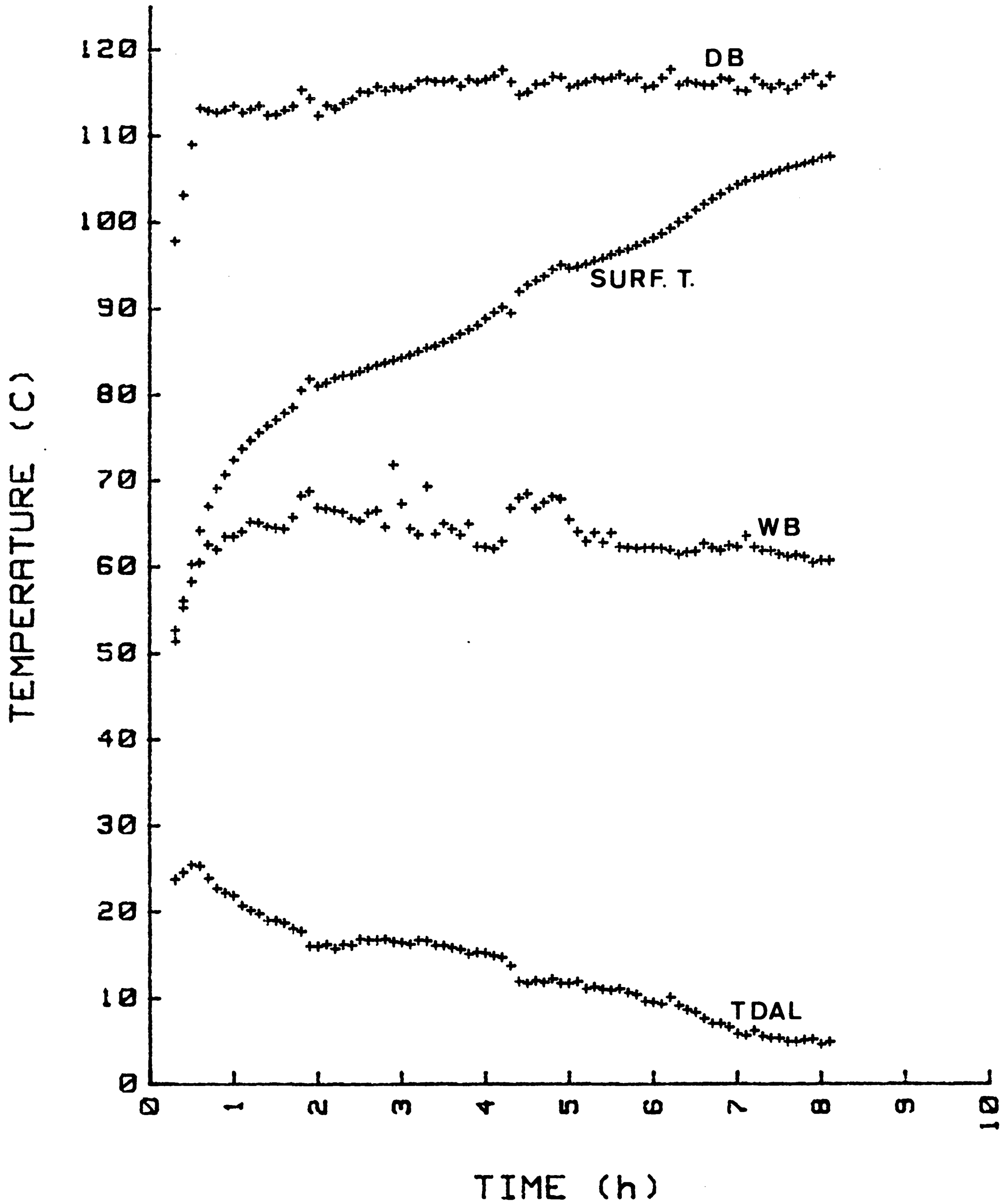

Fig.23 Dry and wet-bulb temperatures, surface temperature and temperature drop across the load, Experiment 3).

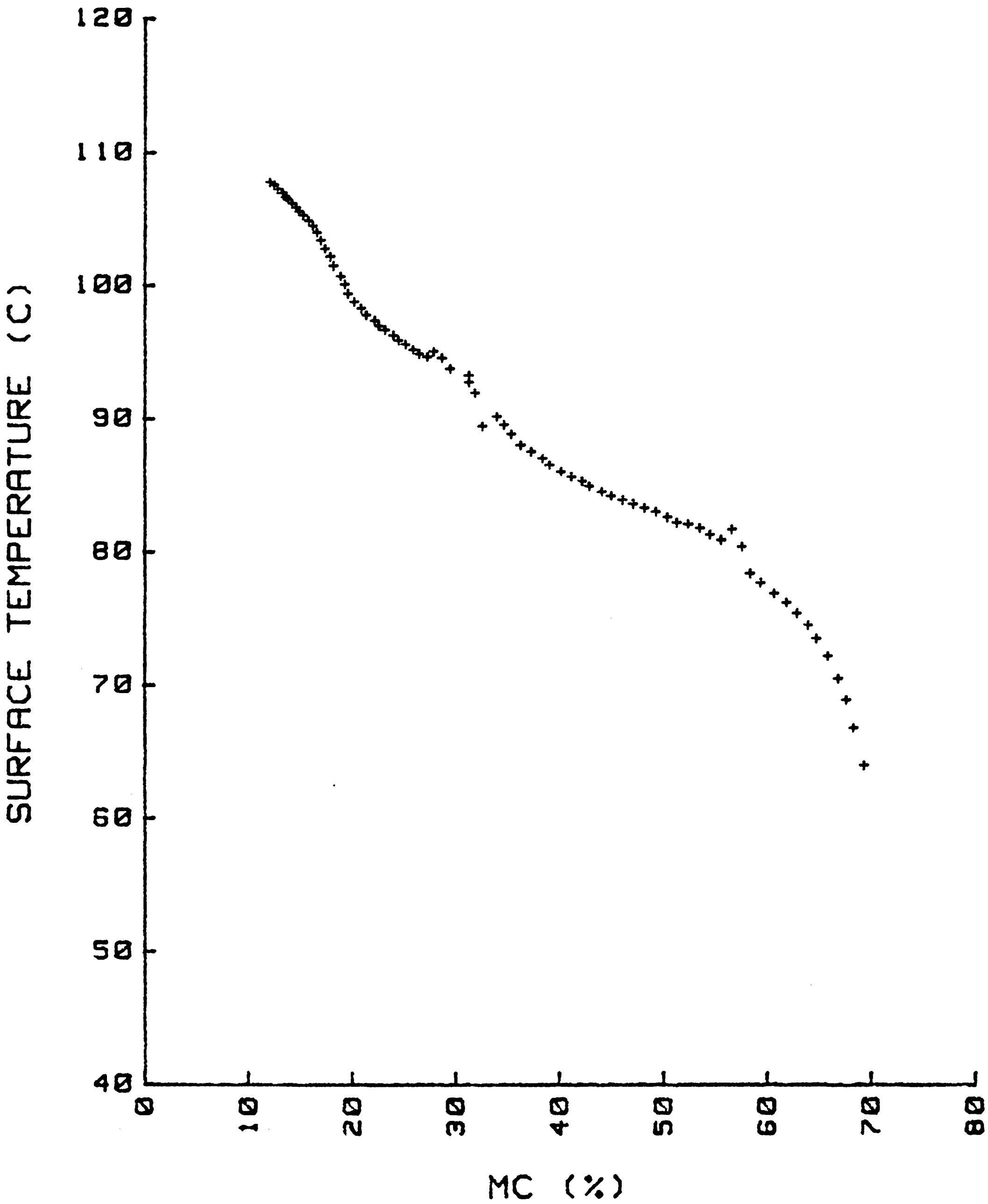

Fig.24 Temperature near the surface of the wood versus moisture content, Experiment 3.

B.4 Experiment No. 4

The drying curve for Experiment 4 is shown in Figure 25. In Experiment 4 and 5, the average initial moisture content was lower than in experiments 1 through 3. The regression equations were:

$MC_4 = 67.6e^{-0.24t}$ ...(R.18)

with SSR = 0.803%

and

$MC_4 = 58.4 - 7.31t$ ...(R.19)

with $r^2 = 0.95$

The predicted values were usually lower than the actual drying rate values (Figure 26).

Figures 27 and 28 present TDAL versus MC and versus Ts. The linear regressions were:

$TDAL_4 = 0.33 + 0.33MC$ ...(R.20)

with $r^2 = 0.96$

and

$TDAL_4 = 54.2 - 0.46MC$ ...(R.21)

with $r^2 = 0.96$

With an α level of 0.05, the intercept of Equation R.20 is not significantly different from zero (t - value = 1.15, df = 68). Therefore Equation R.20 can be simply written as:

$$TDAL_4 = 0.33MC \qquad ...(R.22)$$

The linear regression for Ts versus MC (Figure 30) was:

$$Ts_4 = 117.1 - 0.72MC \qquad ...(R.23)$$

with $r^2 = 0.98$

The convective heat transfer coefficient ranged from 4.8 to 14.5 Btu / (ft^2 h °F) (23.4 Kcal/(m^2 h °C) to 70.8 Kcal/(m^2 h °C)).

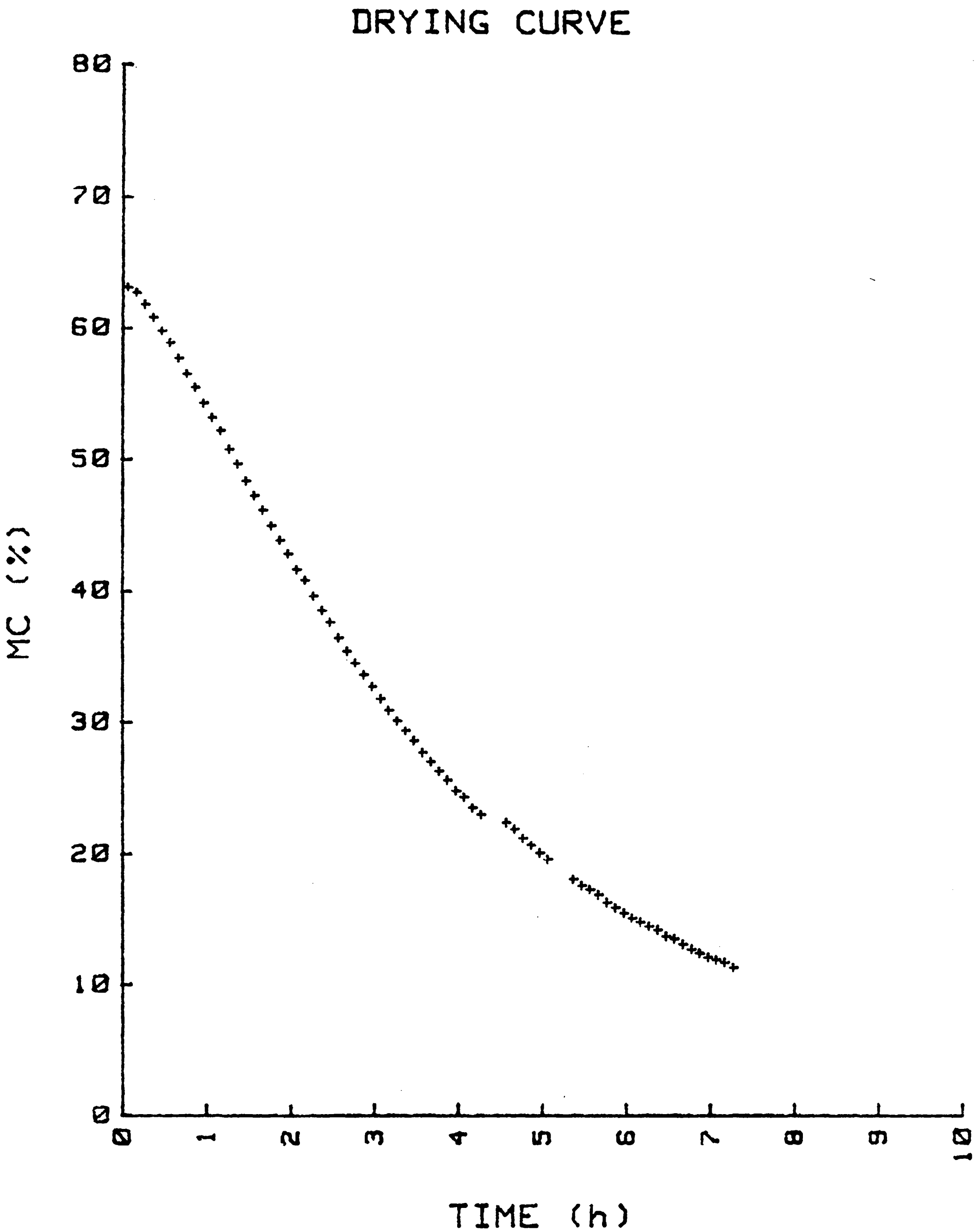

Fig.25 Drying curve, Experiment 4.

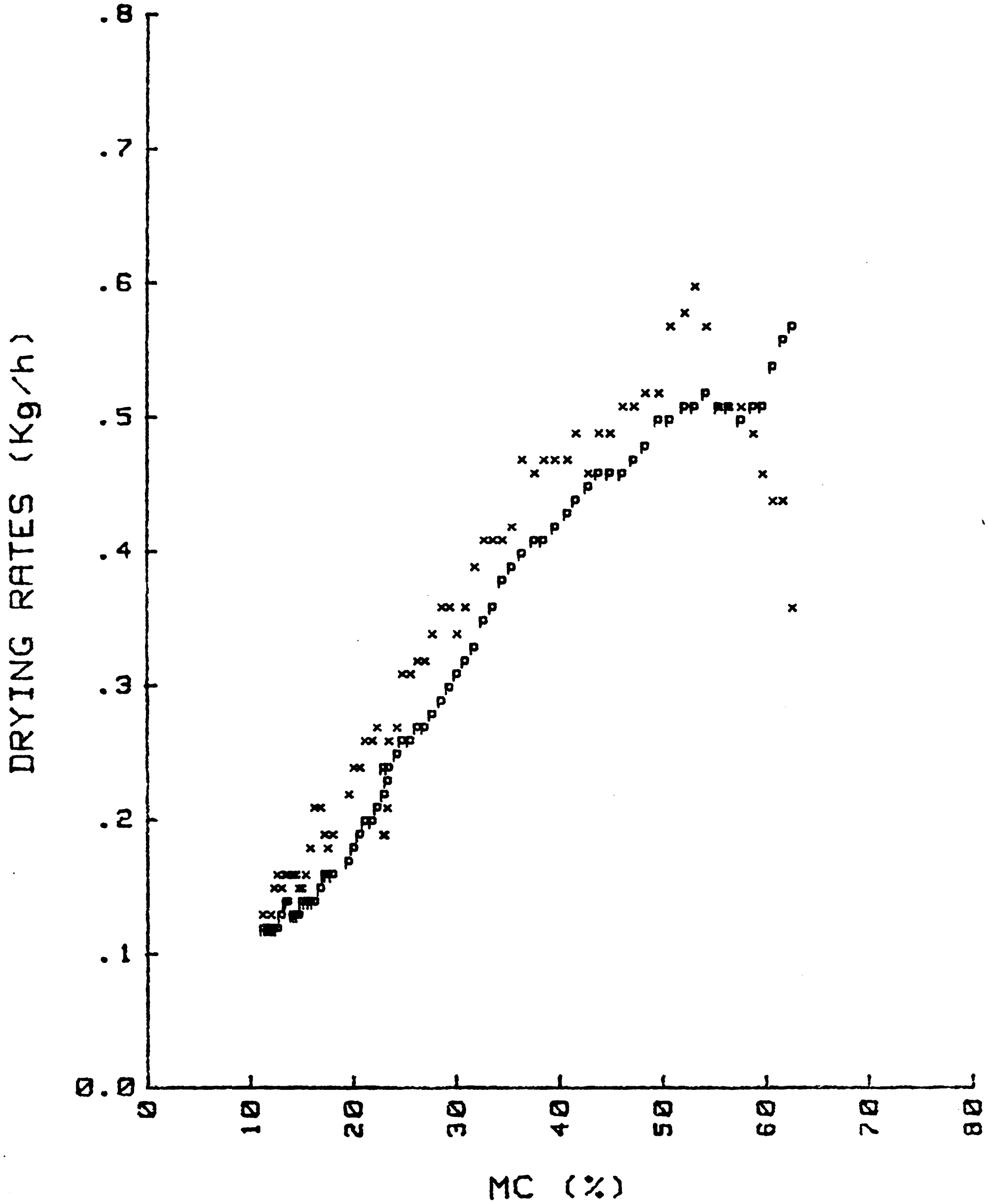

Fig.26 Predicted and observed drying rates (x-observed, p-predicted), Experiment 4 .

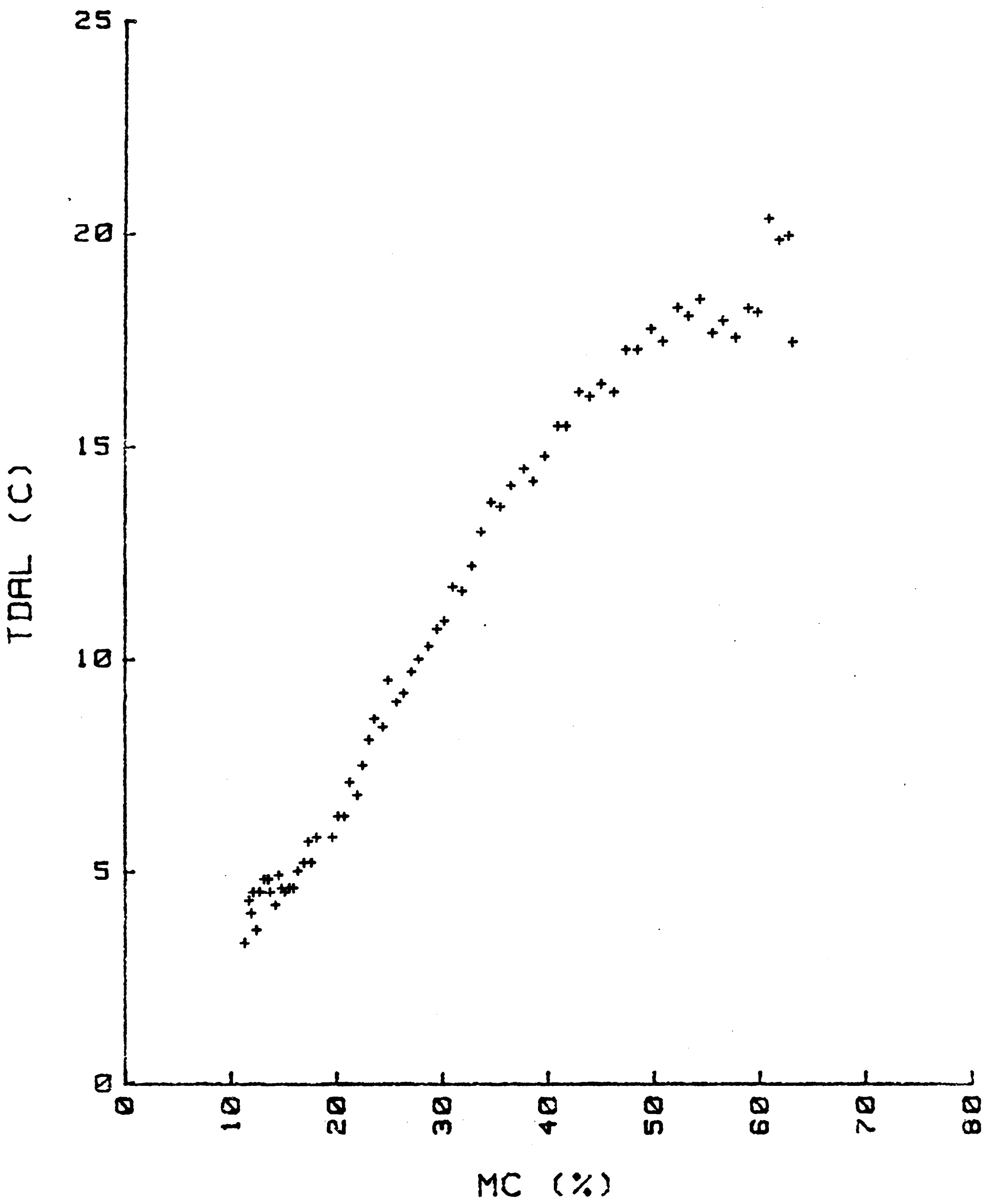

Fig.27 Temperature drop across the load versus moisture content, Experiment 4 .

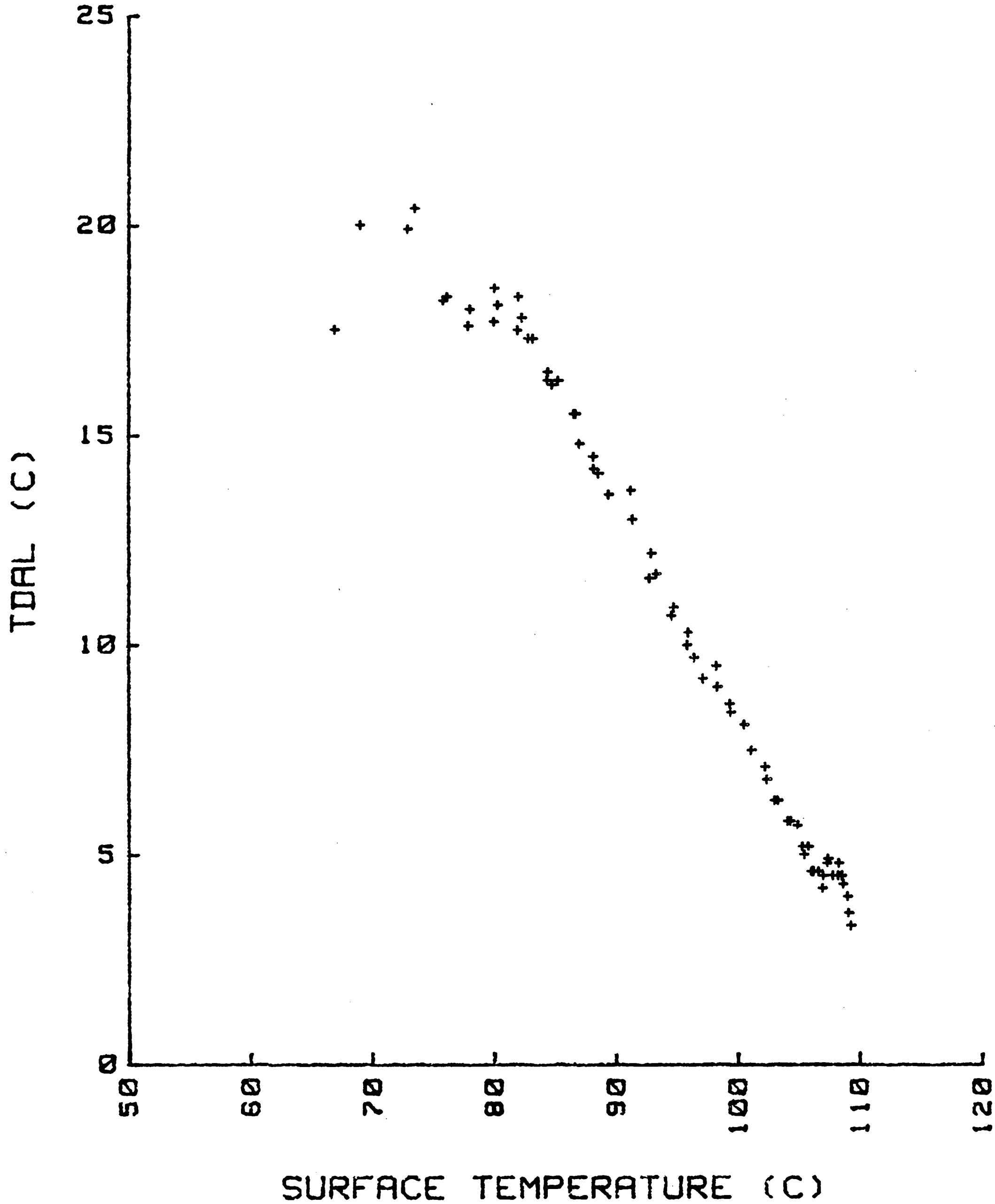

Fig.28 Temperature drop across the load versus temperature near the surface of the wood, Experiment 4.

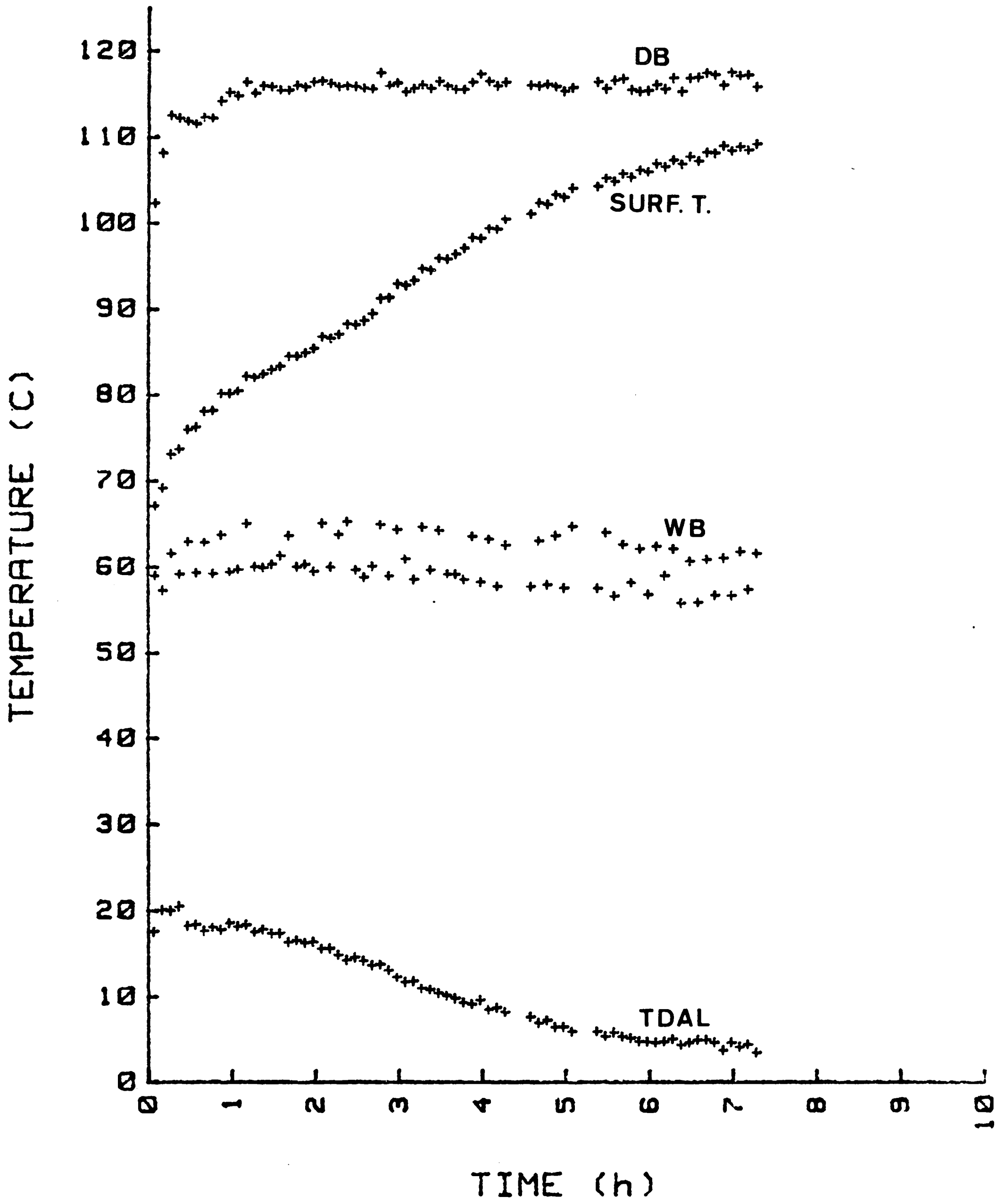

Fig.29 Dry and wet-bulb temperatures, surface temperature and temperature drop across the load, Experiment 4.

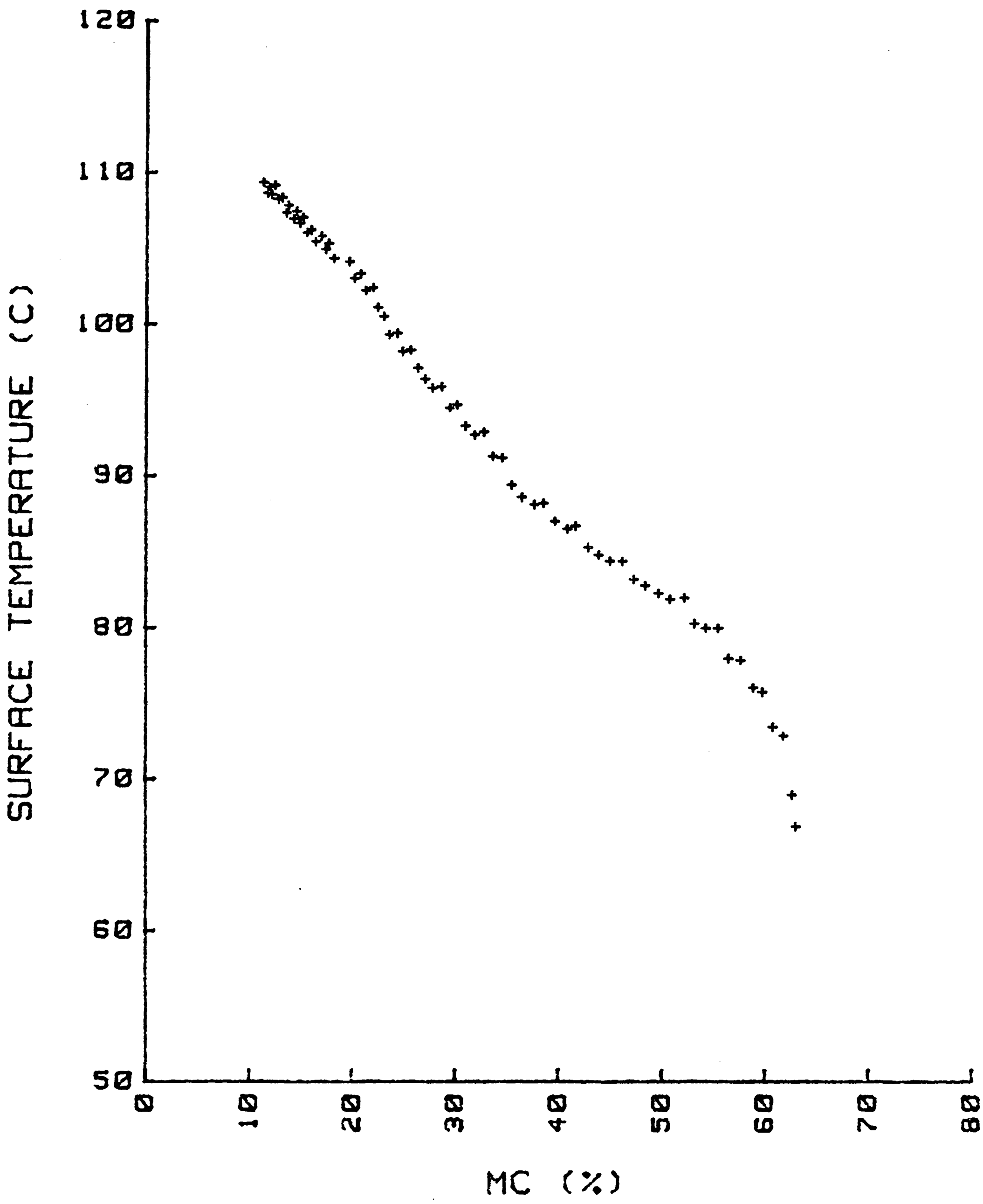

Fig.30 Temperature near the surface of the wood versus moisture content, Experiment 4.

B.5 Experiment No. 5

The drying curve for Experiment 5 is shown in Figure 31. The regression equations were:

$MC_5 = 75.7e^{-0.27t}$ ...(R.24)

with SSR = 1.61%

and

$MC_5 = 61.4 - 7.69t$ ...(R.25)

with $r^2 = 0.95$

The predicted values were close to the observed drying rates (Figure 32), especially for moisture contents below 40%.

Figures 33 and 34 present TDAL versus MC and versus Ts. The linear regression equations were:

$TDAL_5 = 1.5 + 0.39MC$ ...(R.26)

with $r^2 = 0.96$

and

$TDAL_5 = 53.4 - 0.47Ts$ ...(R.27)

with r^2 = 0.93

The linear regression equation for Ts versus MC (Figure 36) was:

$$Ts_s = 109.0 - 0.80MC \qquad ...(R.28)$$

with r^2 = 0.98

The estimated heat transfer coefficient value ranged ranged from 3.8 to 12.1 btu / (ft^2 h °F) (18.6 Kcal/(m^2 h °C) to 59.1 Kcal/m^2 h °C)).

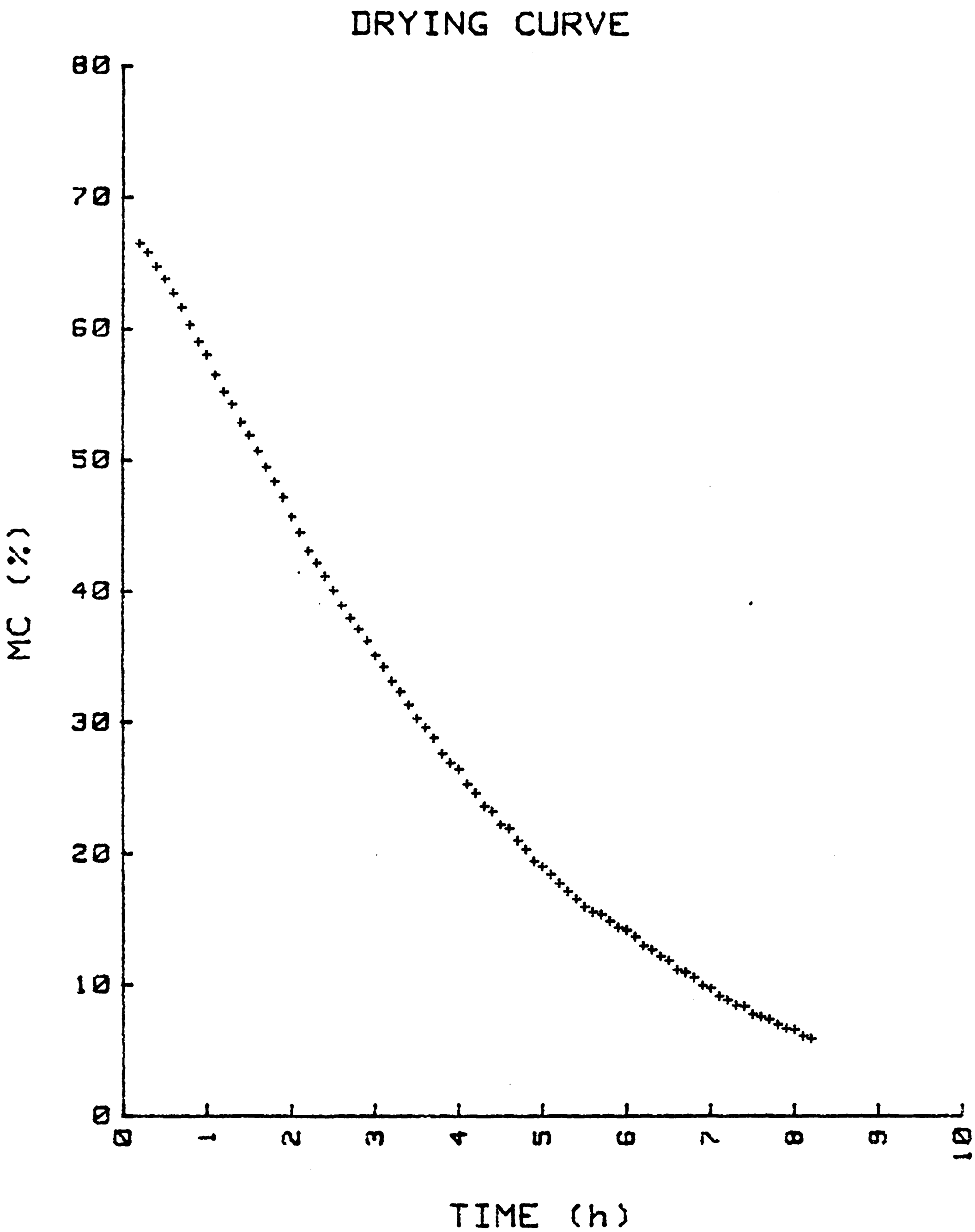

Fig.31 Drying curve, Experiment 5.

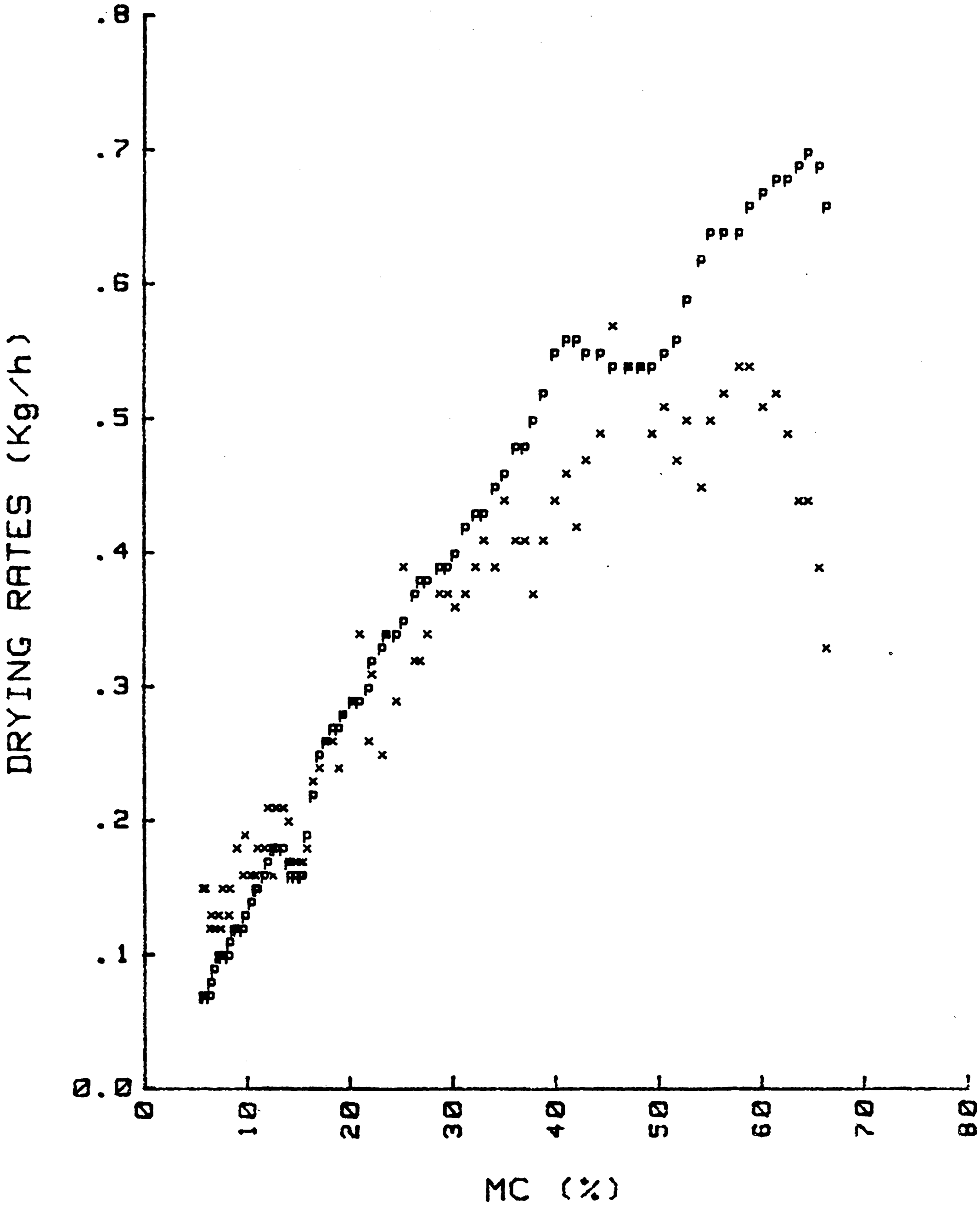

Fig.32 Predicted and observed drying rates (x-observed, p-predicted), Experiment 5.

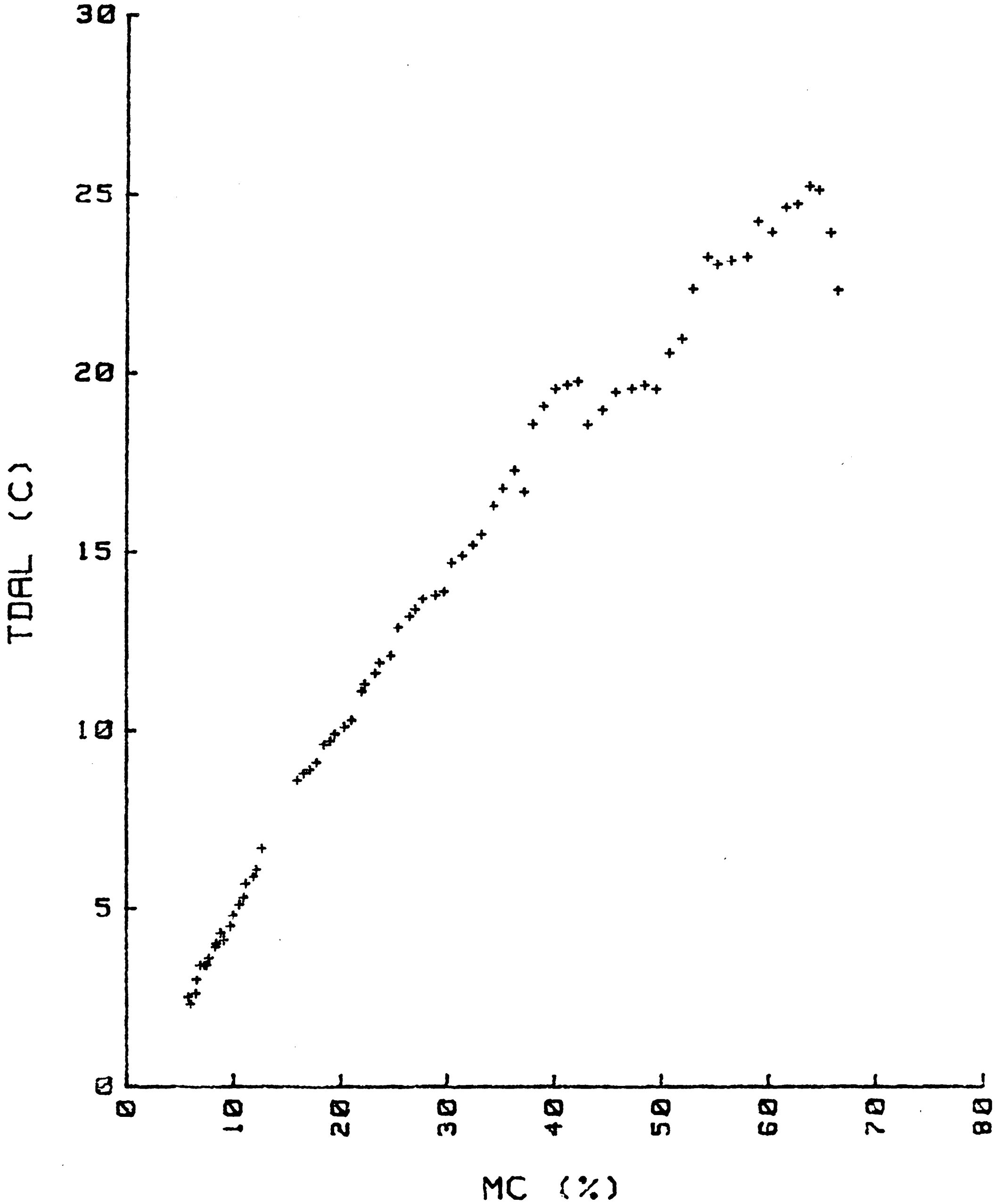

Fig.33 Temperature drop across the load versus moisture content, Experiment 5 .

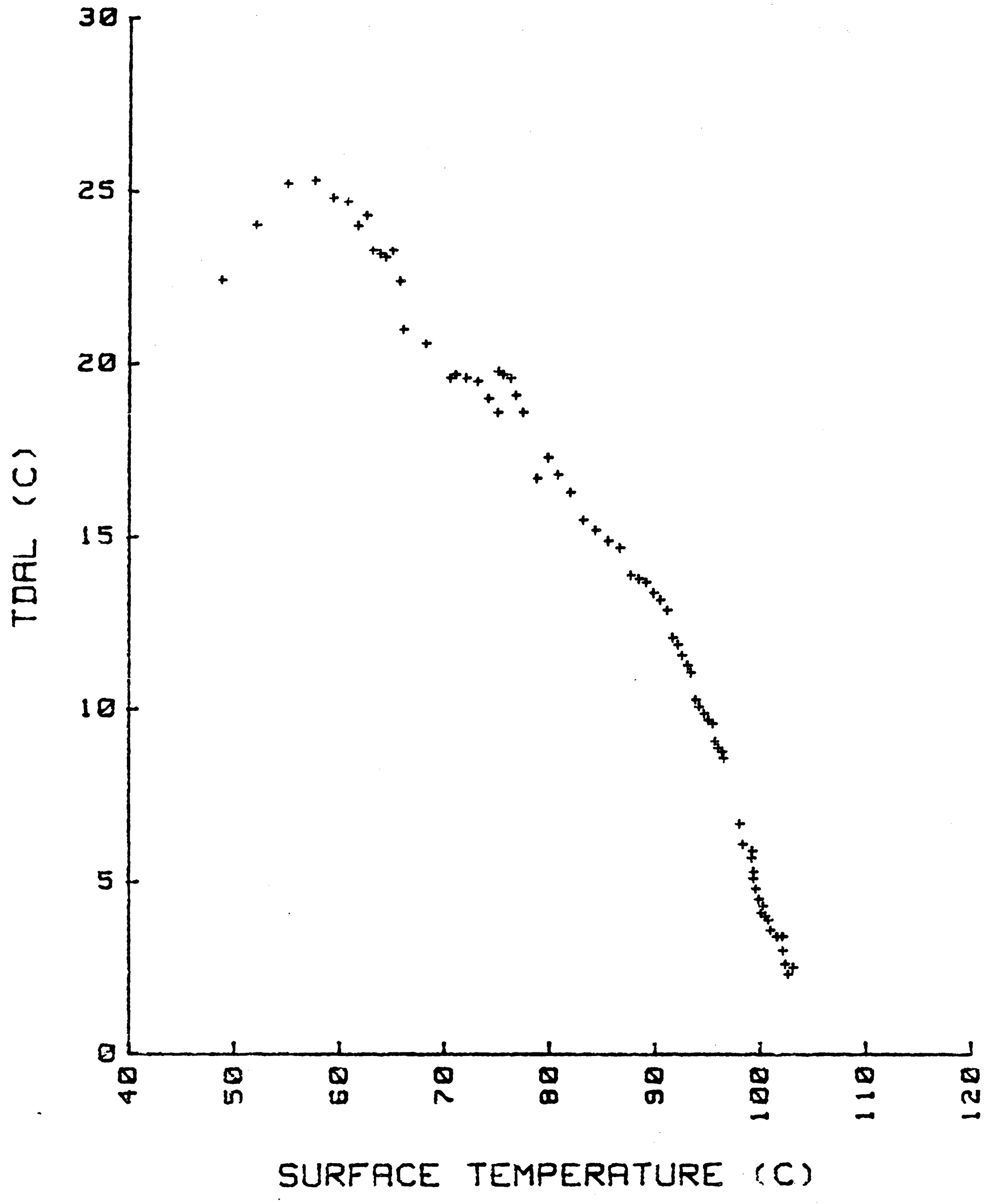

Fig.34 Temperature drop across the load versus temperature near the surface of the wood, Experiment 5.

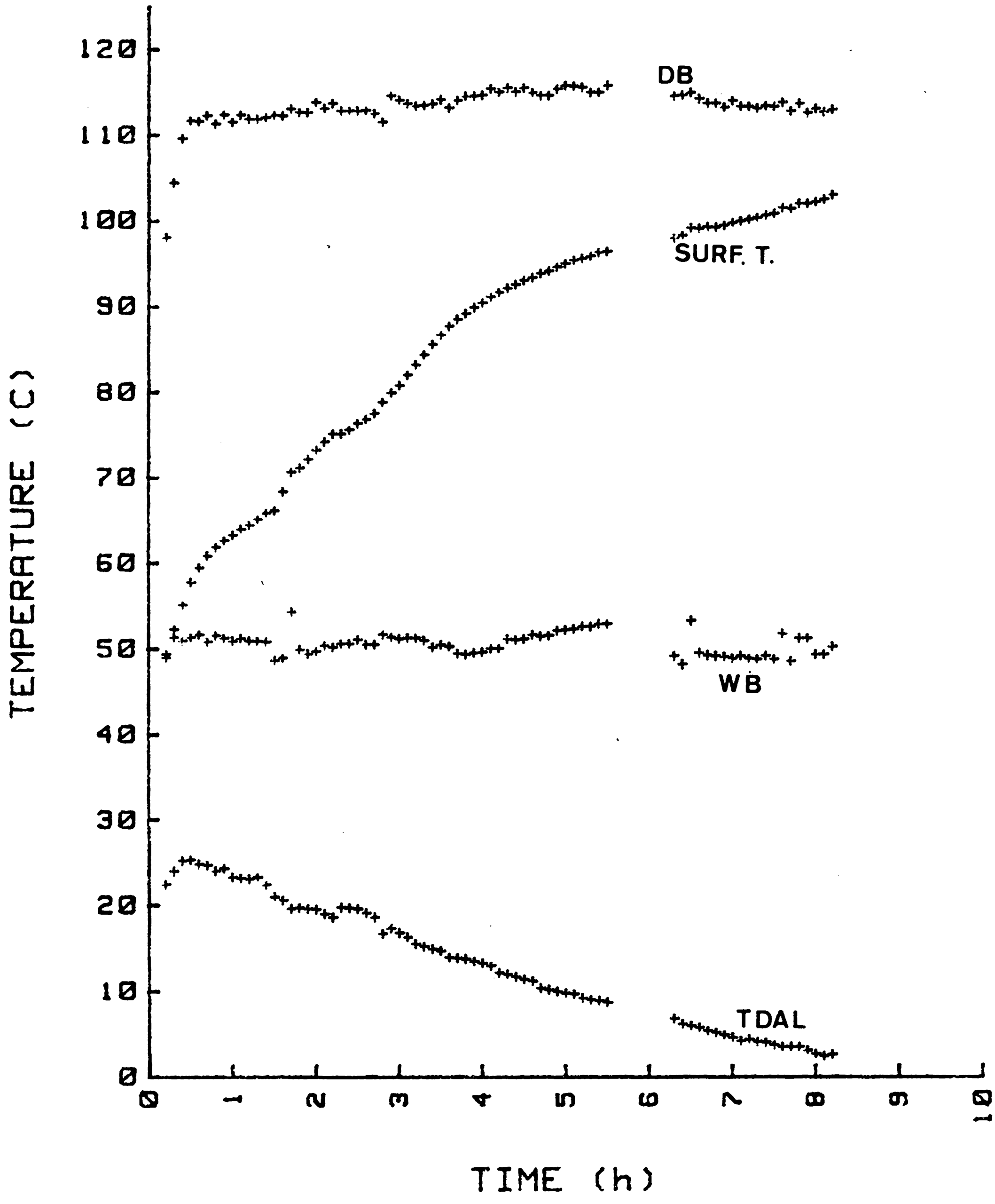

Fig.35 Dry and wet-bulb temperatures, surface temperature and temperature drop across the load, Experiment 5.

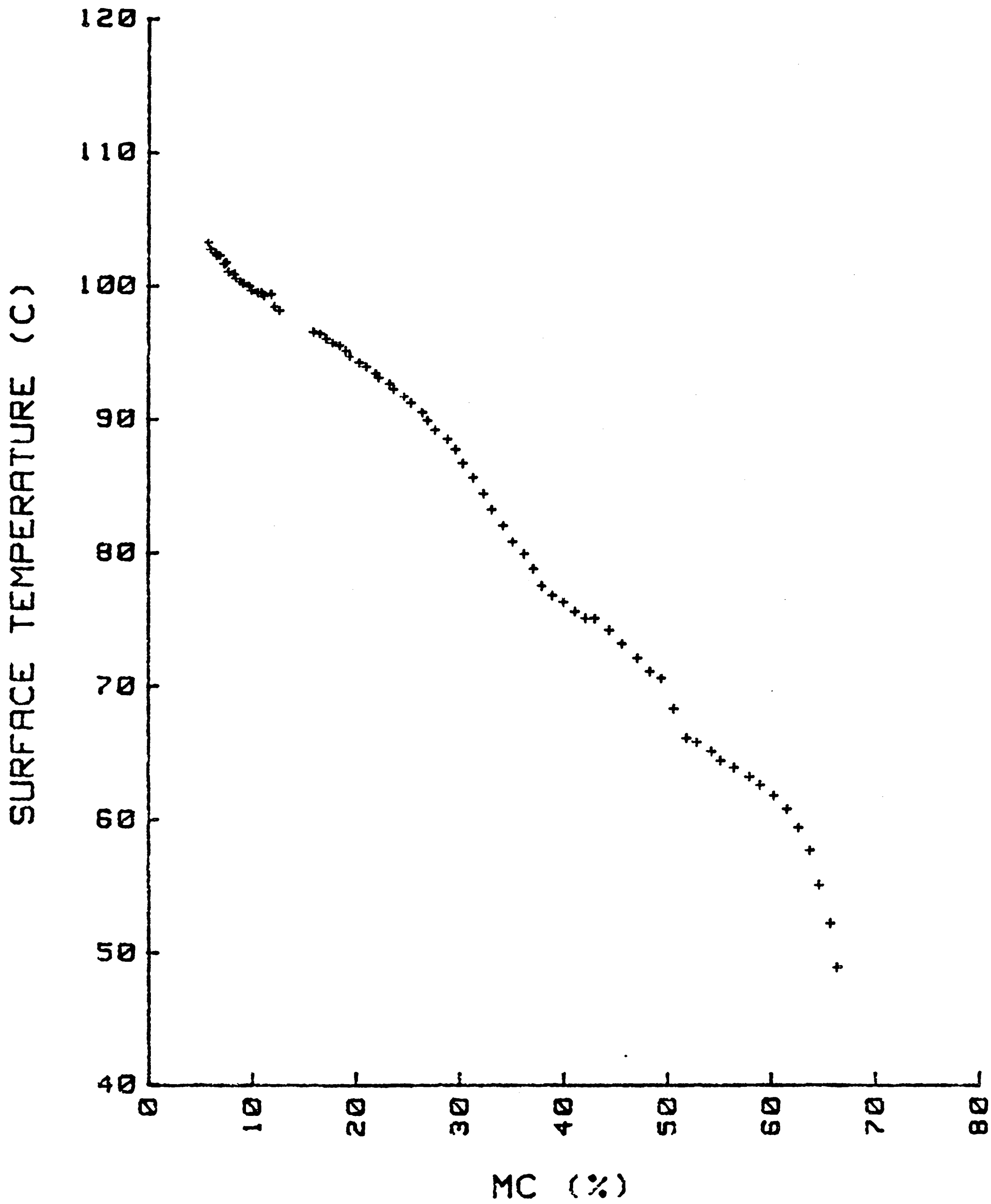

Fig.36 Temperature near the surface of the wood versus moisture content, Experiment 5.

C. General Discussion of Results:

The high temperature drying process was described by only one falling drying rate period which could be approximated by a straight line. It should be pointed out that the drying curves obtained in all experiments represented the average moisture content loss for the entire load of lumber (12 samples). Therefore, although the overall results indicate the existence of only one drying stage or period, it is not possible to infer about the drying behavior of a single sample which might exhibit different drying stages as described by Lowery et al. (1968).

Drying rate values were predicted through the basic mode equation (Equation 34). In order to utilize this equation, the following physical parameters must be known:

- <u>Density of the air and water-vapor mixture ($d_{a.m.}$)</u>:

The density of the air and water vapor mixture was calculated using the average values of dry and wet-bulb temperatures. In doing this, it was implicitly assumed that the specific volume of the air mixture, and therefore its density, was constant along the length of the air travel within the lumber pile. (This is not true, however, because as the air travels along the lumber pile, it will absorb a small amount of moisture which then change the density slightly).

- <u>Velocity of the air</u>: The air velocity was 22,500 ft/h (2 m/s). This was the average air velocity measured with a hot wire anemometer in the middle of the lumber pile.

- <u>Specific heat capacity of the air and water-vapor mixture (Cp_{am})</u>: Specific heat capacity of an air mixture increases as the humidity of the air is increased. Due to moisture absorption, it is expected that Cp_{am} will increase slightly along the air flow path.

- <u>Latent heat of vaporization (L_v)</u>: As the temperature of the wood changes continuously throughout the drying process (Figures 11, 17, 23, 29 and 35), the value of L_v will change by 0.58 Btu/lb °F) (0.58 Kcal/Kg °C). An value for L_v of 1000 Btu/lb (555 Kcal/kg) was used the drying process. This resulted in higher drying rate values in the beginning of the drying process and lower values toward the end of drying.

The predicted rates for Experiments No. 1 and No. 3 were close to measured drying rates. In Experiment No. 5

the predicted drying rates at the beginning of the process were higher than the observed values. Temperature drop across the load (measured values) did correspond well to the decrease in moisture content. It should be pointed out that temperature drop across the load did relate well to the average moisture content of the entire load throughout the MC range. This fact is extremely important for practical industrial situations because information obtained from a simple relationship of the form TDAL = A + B(MC), can be used to avoid overdrying of the lumber.

C.1 Effect of Wet-bulb on Drying rates: The role of the wet-bulb temperature on high temperature drying of wood, can be established by either of two approaches: effect on quality and effect on drying rates. In this dissertation the effect of wet-bulb temperature on drying rates during high temperature drying of southern yellow pine dimension lumber was investigated.

Drying rates as a function of time for all five experiments performed are given in Figure 37. Linear regression analysis for each experiment resulted the equations presented in Table 2. As indicated by the r^2 coefficients, drying rates for most of the drying process

Table 2. Regression coefficients for drying rates (D) (Kg/h) versus drying time (t) (h). Model: D = A + Bt

Experiment No.	DBT °C	WBT °C	Regression Coefficient A	B	R^2
1	116.6	67.9	0.63	-0.035	0.75
2	116.8	65.1	0.72	-0.045	0.78
3	115.0	63.7	0.60	-0.068	0.87
4	115.4	60.5	0.56	-0.050	0.71
5	113.3	50.5	0.59	-0.062	0.77

DBT = dry-bulb temperature.

WBT = wet-bulb temperature.

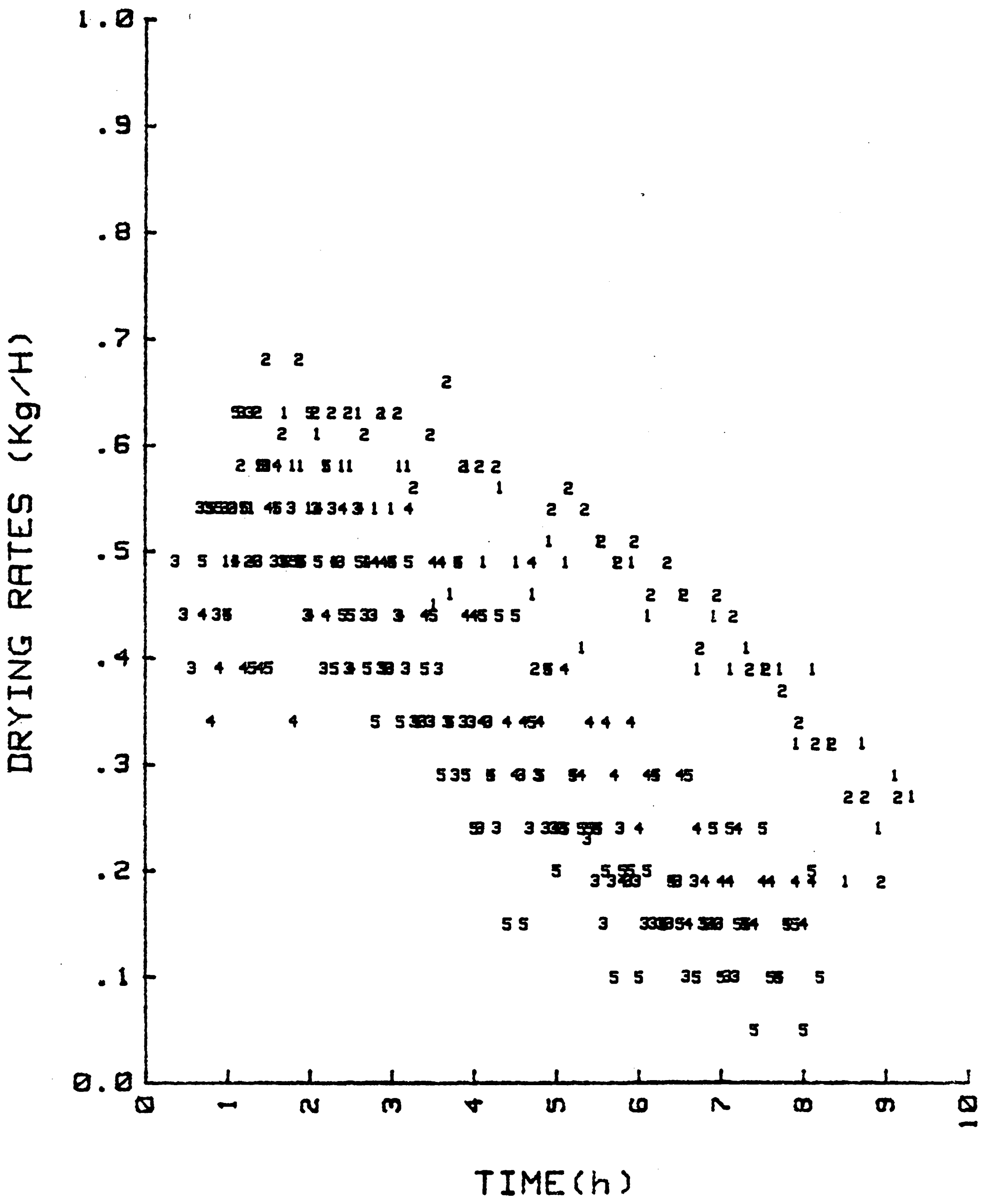

Fig. 37 Observed drying rates (Experiments 1, 2, 3, 4 and 5).

were reasonably well explained by the linear regressions obtained.

The graphs (Figure 37) suggest that the data can be divided into two major groups. The upper region is represented by the data obtained in Experiments 1 and 2; the lower group by Experiments 3, 4 and 5.

Assuming an homogeneous error variances for all regressions presented in Table 6, an F test was used to test the hypothesis that the slopes were not significantly different. The computed pooled mean square error (MSE) and the mean square error for the variable being tested (MSSlope) were:

MSE = 0.004

MSSlope = 0.003

At α level 0.05, the F value for $df_1 = 4$; $df_2 = 300$ is approximately 2.4. The calculated F value (MSSlope/MSE) is 0.750 which is smaller than the tabulated F value. Therefore, the hypothesis can not be rejected, and as a result the slopes of the regression equations are not significantly different. Therefore wet-bulb temperature from approximately 50°C to 70°C, did not affect drying rates.

C.2 <u>Convective Heat Transfer Coefficient</u>: The estimated heat transfer coefficients throughout each experiment, are presented in Figures 38, 39, 40, 41 and 42. In estimating convective heat transfer coefficients through Equation 37, it was assumed that the measured temperature near the surface (1.6 mm below) represented the temperature of the surface of the wood. Latent heat of vaporization which depends on surface temperature and the dry-bulb temperature for any position in the lumber pile will vary throughout the drying process. The difficulty of estimating accurate values for these two parameters introduce errors when predicting convective heat transfer coefficients through Equation 37. As it can be seen from these figures, the convective heat transfer coefficients were usually higher when drying was carried out at higher wet-bulb temperatures and high moisture contents (Experiment Nos. 1 and 2).

Combining the data for Experiments 1 and 2 (wet-bulb temperatures of approximately 68°C and 65°C respectively), the convective heat transfer coefficient ranged between 7.2 Btu/(ft^2 h °F) to 24.1 Btu/(ft^2 h °F) (35.2 Kcal/(m^2 h °C) to 117.7 Kcal/(m^2 h °C)) with an average of 16.2 Btu/(ft^2 h °F) (79.1 Kcal/(m^2 h °F).

Figures 40, 41 and 42 indicate that h did not consistently increase as the drying progressed. Combining the data from those figures (Experiments 3, 4 and 5), the minimum value for h was 3.8 Btu/(ft^2 h °F) (18.6 Kcal/(m^2 h °C)) and the maximum was 14.5 Btu/(ft^2 h °F) (70.8 Kcal/(m^2 h °C)) with an average of 8.9 Btu/(ft^2 h °F) (43.4 Kcal/(m^2 h °C)).

C.3 <u>Heat and Mass Transfer</u>: The surface temperature Ts was above the wet-bulb temperature and was continually increasing. If mass transfer were sufficient (or more rapid than heat transfer), then the wood temperature would stay at the wet-bulb temperature and there would be a constant rate drying period. Heat transfer can be slowed (Equation 27) by reducing Ta - Ts, or specifically raising the wet-bulb temperature. Therefore, at higher wet-bulb temperatures, it would be expected that a constant rate period might be observed, such as indicated by Wengert (1984a) with wet-bulb temperature greater than 200 °F (93.3 °C).

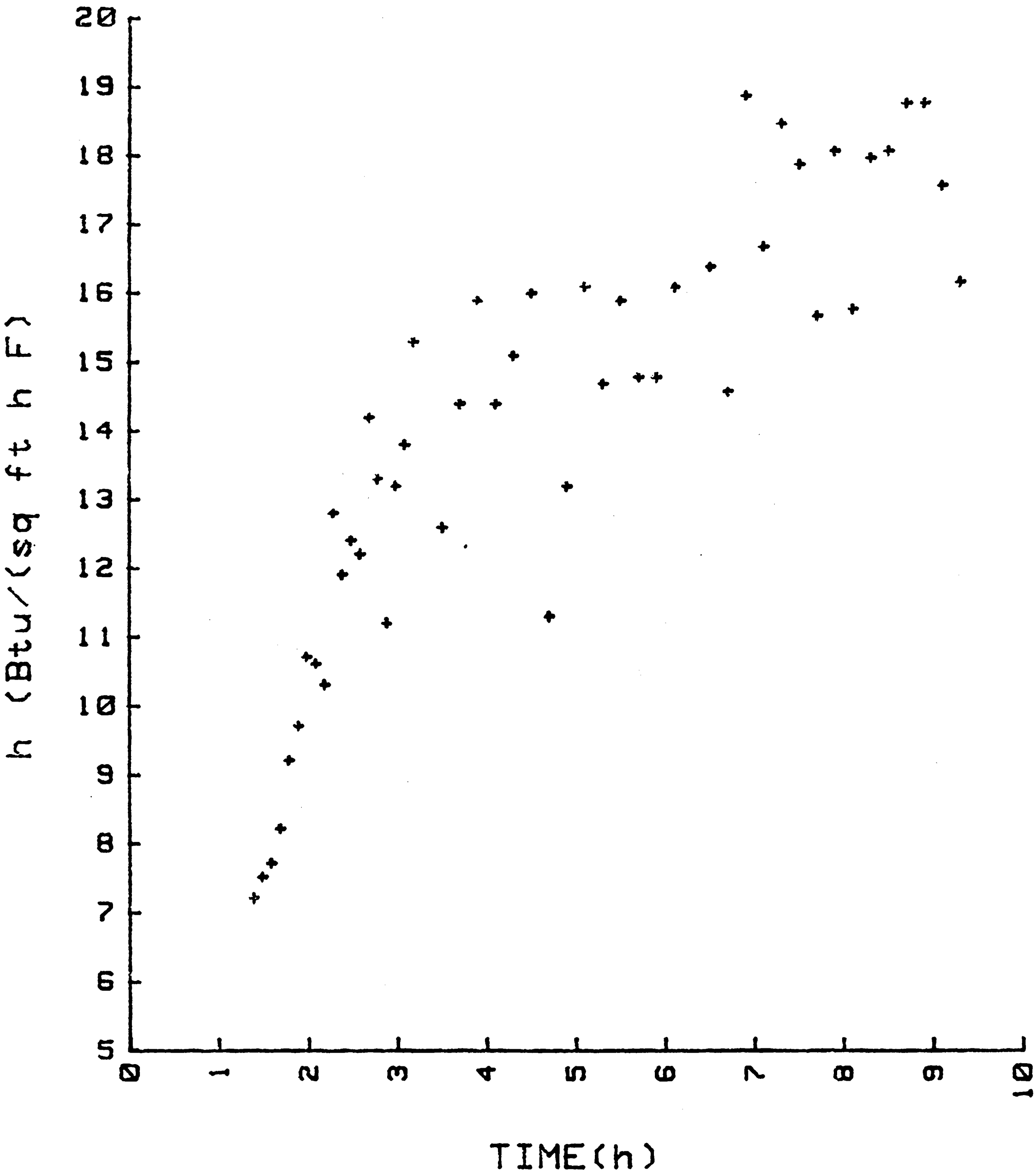

Fig.38 Heat transfer coefficients (Experiment No.1).

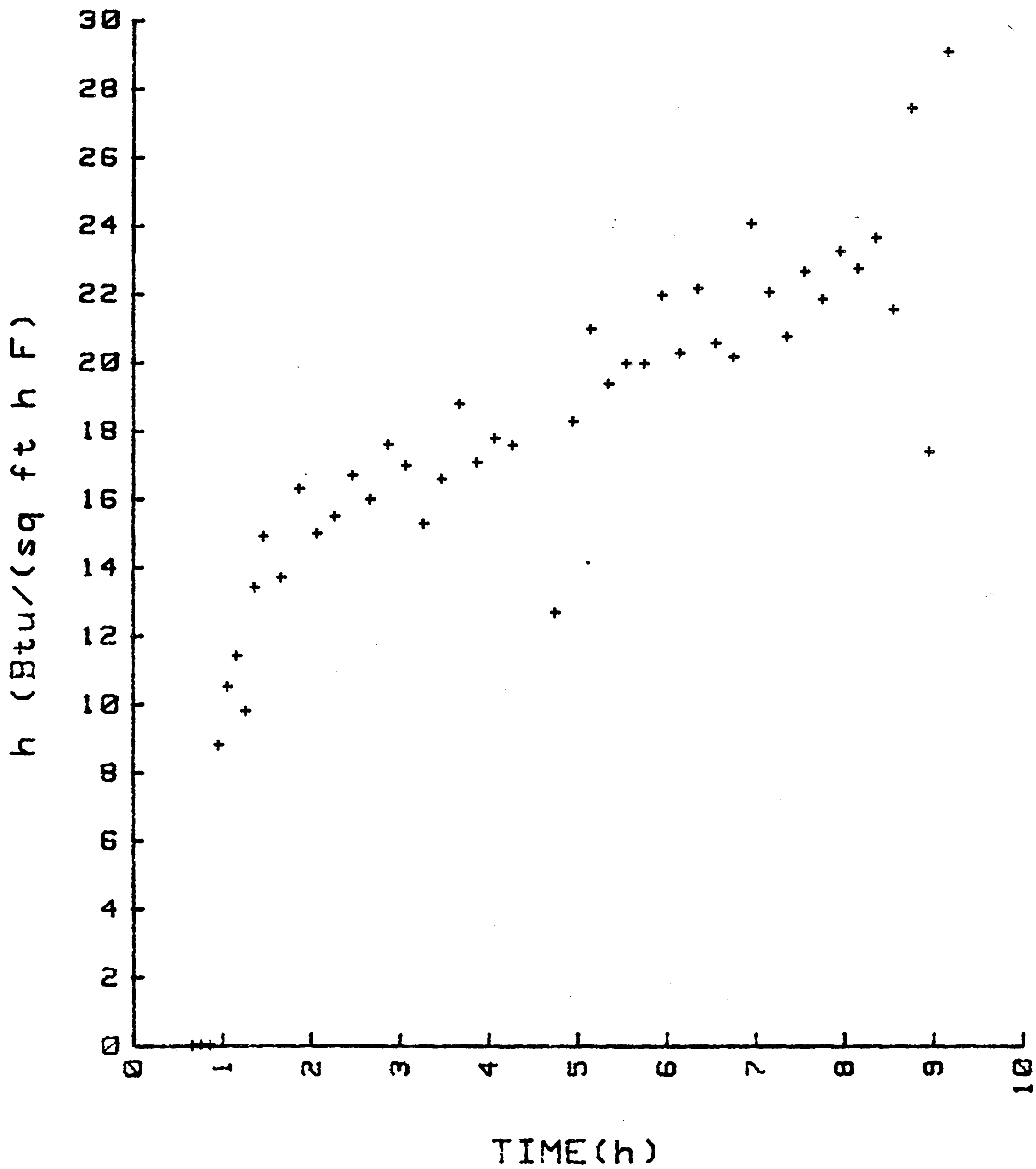

Fig.39 Heat transfer coefficients (Experiment No.2).

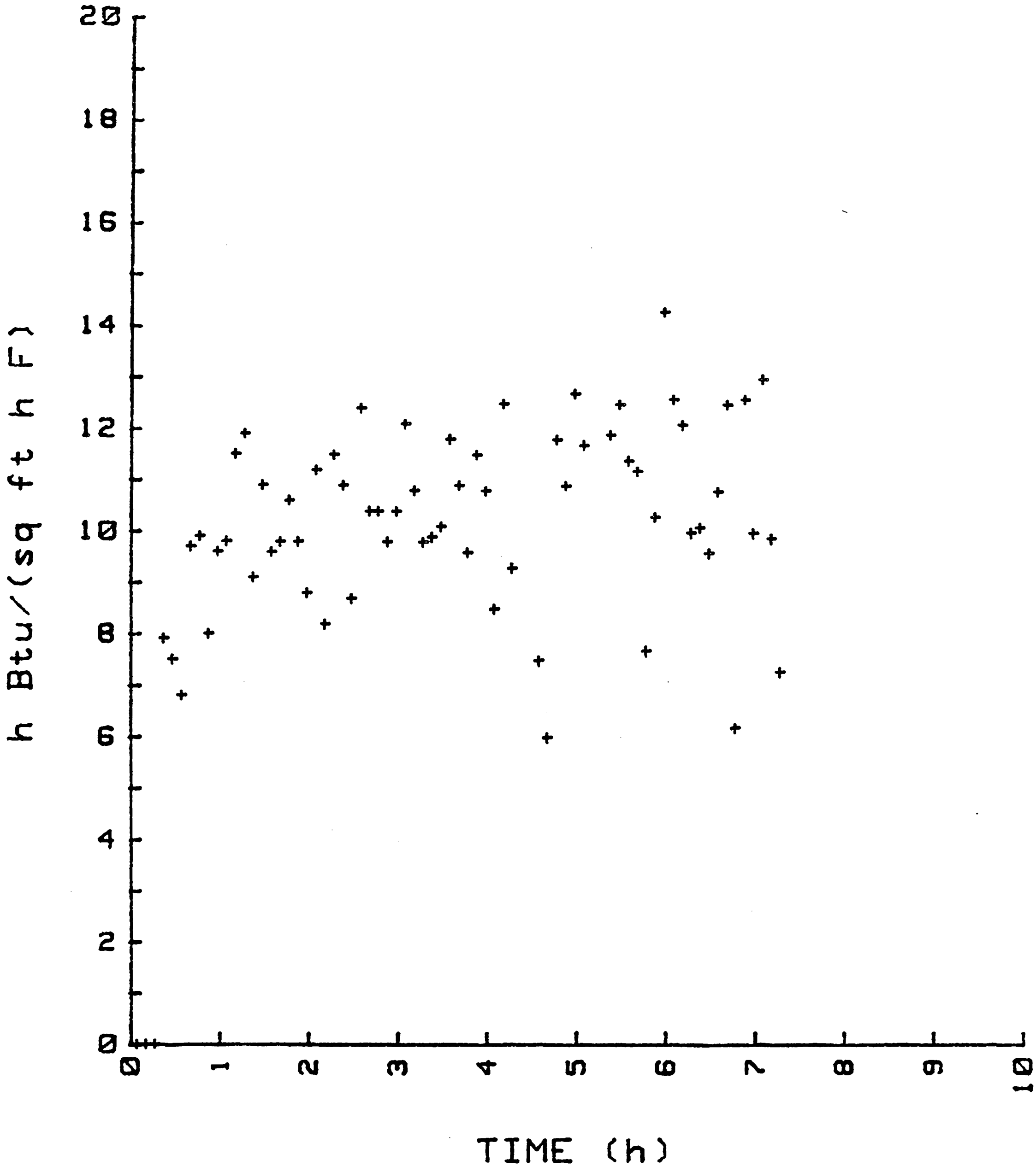

Fig.40 Heat transfer coefficients (Experiment No.3).

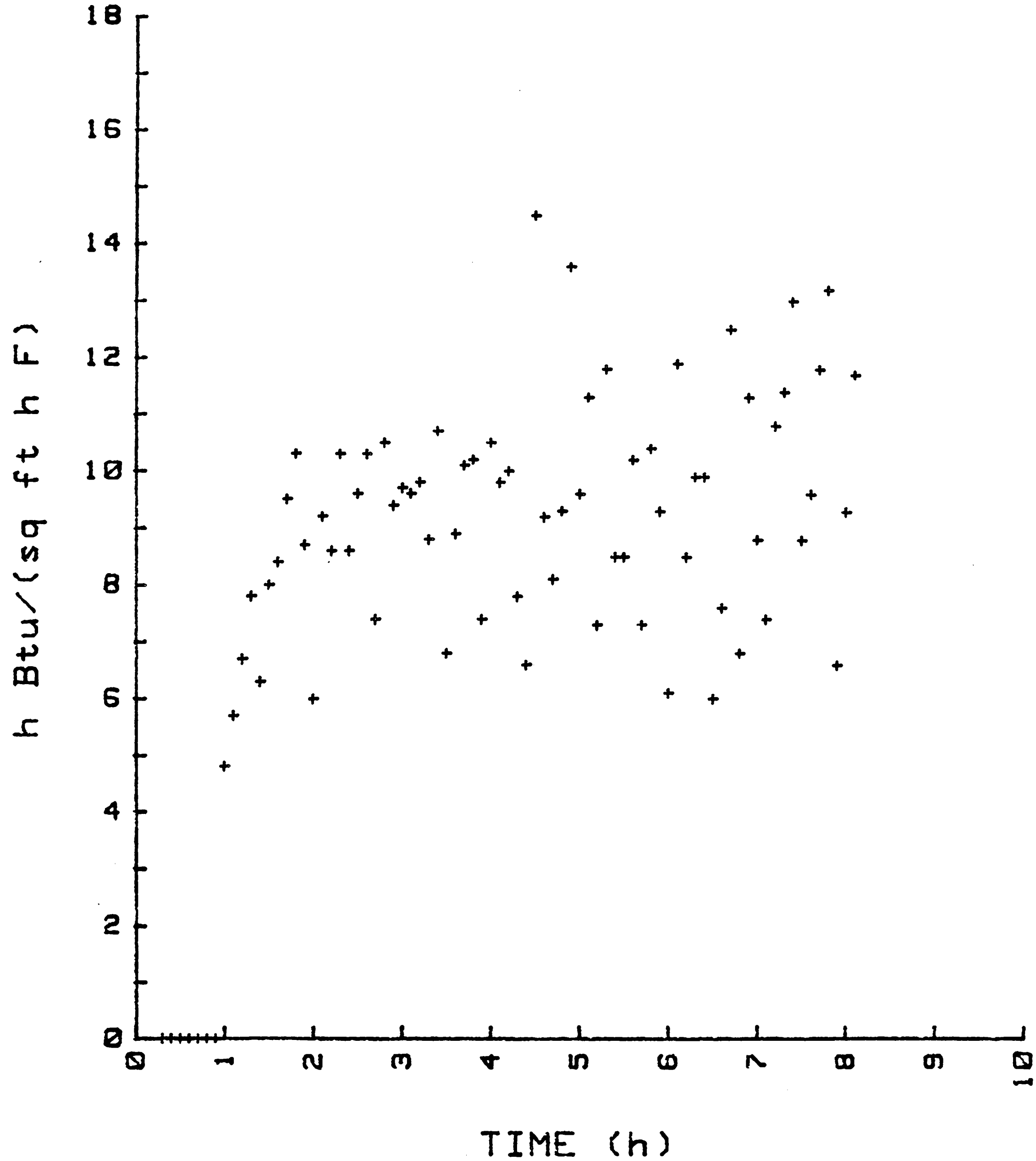

Fig.41 Heat transfer coefficients (Experiment No.4).

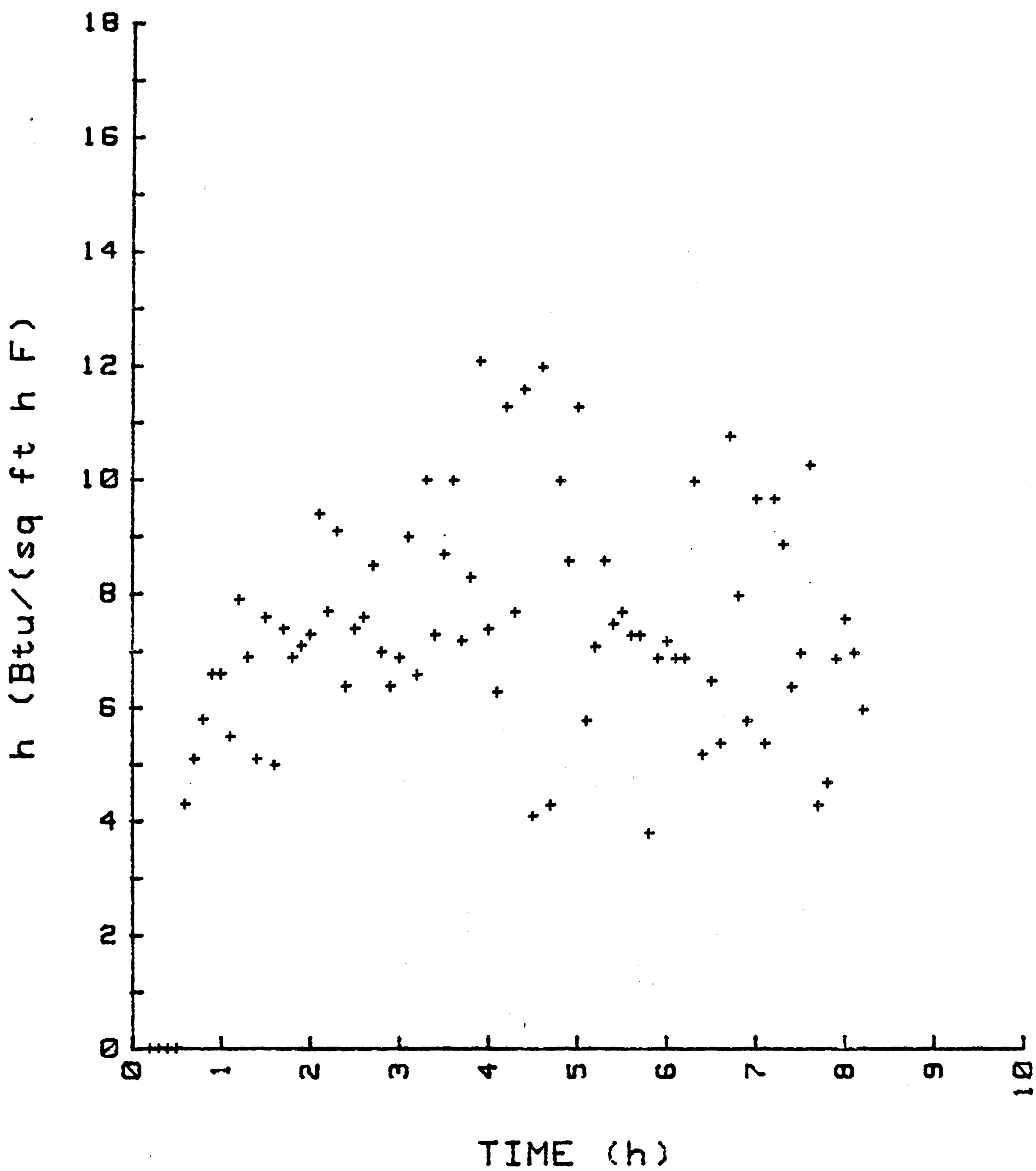

Fig.42 Heat transfer coefficients (Experiment No.5).

CHAPTER NINE

SUMMARY AND CONCLUSIONS

In convective high temperature drying of southern yellow pine, very complex interaction between heat and mass transfer exists within the wood. The physical properties of wood such as density, latent heat of vaporization and specific heat capacity, change throughout the drying process due to the variation of temperature and moisture content.

The adoption of the concept expressed by the Lewis number to establish the relationship between heat and mass transfer, indicated that during convective high temperature drying of southern yellow pine, resistance to mass transfer is greater than resistance to heat transfer. Therefore, probably for the most part of the drying process of southern yellow pine dimension lumber at dry-bulb temperature of 115 °C and wet-bulb temperature ranging from 50 to 70 °C, mass transfer within the wood is the limiting or controlling factor for the overall drying.

It is interesting to note that Hann (1964) intuitively hypothesized that heat transfer was the limiting factor throughout the drying of yellow-poplar. A direct consequence of this is that drying rates decrease during the drying process primarily due to the difficulty of transferring heat energy within the wood.

The results of this study at dry-bulb temperature of 115 °C and wet-bulb temperature ranging from 50 °C to 70 °C indicated that the drying process was characterized by only one decreasing drying rate stage. A true "constant drying rate period" was not observed.

Exponential functions ($MC = Ae^{-Bt}$) described the decrease of moisture content throughout the process. However, for practical purposes, the drying curves can also be described by simple linear functions ($MC = A' + B't$).

Observed temperature drop across the load (TDAL) related well to average moisture content and to the temperature near the surface of the wood. The TDAL versus MC relationships can potentially be used for drying process control and for evaluation of the effects of temperature on mechanical properties of wood.

The temperature near the surface of the wood increased continuously during all drying experiments and was always above the wet-bulb temperature. In all experiments, there was a strong relationship between the temperature near the surface of the wood and average moisture content. Therefore, knowledge of this temperature during the drying process could be used to avoid overdrying.

Convective heat transfer coefficients were within the range 3 Btu/(ft^2 h °F) (14 Kcal/(m^2 h °C)) to approximately 25 Btu/(ft^2 h °F) (120 Kcal/(m^2 h °C) but did not vary significantly with MC. This is the range normally cited in the literature for heat transfer involving forced convection. For practical purposes, the convective heat transfer coefficient for most of the drying process carried out at low wet-bulb temperatures can be taken as a constant value.

Finally, the idea of utilizing the concept of temperature drop across the load originally suggested by Wengert (1984a) did produce reasonably good results for predicting drying rates. In all experiments performed, except during early stages of the drying process, drying rates predicted through the temperature drop across the load equation were very close to the measured values.

CHAPTER TEN

RECOMMENDATIONS

The results of this study indicated that due to the rapid water removal during convective high temperature drying of southern yellow pine, moisture transfer within the wood, for much of the drying period, was main constraint of the process.

Drying rates predicted through the temperature drop across the load equation did correspond to the actual measured values obtained in the drying experiments. However, in order to successfully use the temperature drop across the load model, it is necessary to obtain a better description with respect to the variation of the drying conditions of temperature and relative humidity along the lumber pile, especially during the earlier stages of drying. Therefore, it is suggested to investigate drying rates during the heating-up period of the high temperature drying process. This information would permit to obtain a better temperature drop across the load equation which then, could be used for controlling purposes during the entire drying process.

CHAPTER ELEVEN

PRINCIPLES OF A CONTROL SYSTEM BASED ON TEMPERATURE DROP ACROSS THE LOAD

The control operation during lumber drying is intended to maintain the fastest drying rate possible without exposing the wood to conditions of high risk of degrade development. Yet, the control action must be performed in a such way to assure that the moisture content of the entire load of lumber at the end of the drying process is uniform and at the desired target level.

A proper controlled drying operation will reduce the overall drying cost due to a better quality of the lumber. This latter advantage not only leads up to a reduction in the energy consumption, but also avoid unnecessary extended drying. The difficulty in controlling the high temperature drying of southern yellow pine may be attributed to the following factors: a) non-uniformity in initial moisture content for the load of lumber to be dried, b) arrangement and stacking procedures of the lumber inside the dryer and c) dryer.

In practical industrial situations, it is very common to observe a large variation of the initial moisture of southern yellow pine dimension lumber. Presorting the lumber is then necessary to reduce initial moisture content variation of the load to be dried.

Stacking procedures prior to drying will play a decisive role in providing a more uniform rate of drying and avoiding degrade development during the process. General rules for satisfactory stacking of the lumber include sticker dimensions, moisture content, location, horizontal spacing and alignment along the height of the load of lumber.

The thickness of the sticker determines the spacing between two layers of lumber and therefore, it determines the rate of air flow through the load. Heat transfer to the lumber and consequently the rate of water removal will not be uniform if the lumber is not equally spaced during the stacking procedure. Inadequate sticker horizontal spacing and alignment along the height of the load of lumber, may cause warp degrade which in turn, distorts the spacing between the lumber resulting in non-uniform rate of drying.

Dryer designs features such as insulation, location of dry wet-bulb temperature sensors, heating, venting and air circulation systems will greatly influence drying rates throughout drying and thereby determine the overall control over the process.

From the facts discussed above, it can be seen that due to the complexity of the interaction among lumber and dryer factors, a successful control operation is rather difficult to achieve with the standard techniques currently in use during high temperature drying of southern yellow pine dimension lumber.

The utilization of the temperature drop across the load (TDAL) appears to be an important alternative for controlling purposes during high temperature drying of southern yellow pine dimension lumber. As it was experimentally determined during the high temperature tests described in previous sections, the TDAL did relate well to average drying rates, average moisture content and temperature near the surface of the wood. These results emphasize the potential of TDAL in predicting and comparing drying rates, estimating moisture content and monitoring wood temperature throughout the drying process.

The TDAL technique requires only the measurements of dry-bulb temperatures in the lumber pile. Therefore it will overcome the difficulty in practically measuring moisture contents as the drying progresses. Another advantage of utilizing the TDAL technique is that it produces a rapid evaluation of drying rates and moisture content. In addition, total energy usage can be estimated by substituting the TDAL into Equation 41 and integrating it with respect to time.

Based on the information that can be obtained by measuring TDAL, the following principles of a control system can be described:

- Figure 43 depicts a side view of a two-track steam-heated dryer . In this example, each pile is 8 ft wide (2.4 m) (x-direction) 12 ft long (3.7 m) (z-direction). The heating system (heating coils) is vertically and horizontally distributed along region I, II and III according to the following: in all regions I, II and III, there are 4 heating zones along the length of the pile (z-direction) and 3 heating zones along the height (y-direction). This arrangement provides a total of 12 independent heating zones for each pile. When air is flowing from region I to region III, the heating system on region III is not activated. The heating systems located in regions I and III are actually auxiliary heating units of the main heating system A and B located at the upper part of the dryer.

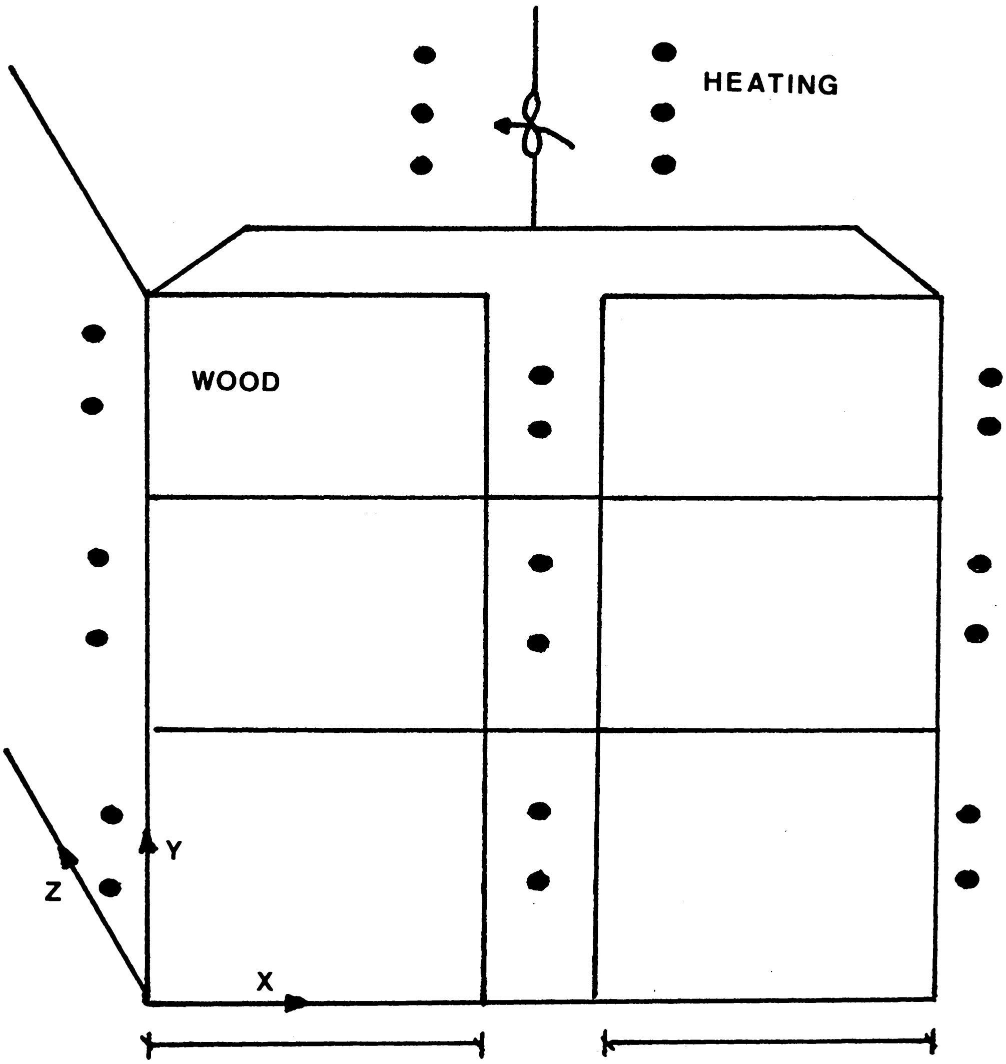

Fig.43 Schematic representation of a two-track lumber dryer with main heating zones.

Schematically the TDAL measuring points are divided according to:

```
        TDAL_A                              TDAL_B
           |                                   |
 ---------|---------                 ---------|---------
 |         |         |               |         |         |
 |         |         |               |         |         |
top     middle    bottom            top     middle    bottom
 |         |         |               |         |         |
---|---   ---|---   ---|---         ---|---   ---|---   ---|---
| | | |   | | | |   | | | |         | | | |   | | | |   | | | |
1 2 3 4   1 2 3 4   1 2 3 4         1 2 3 4   1 2 3 4   1 2 3 4

   MEASURING POINTS                    MEASURING POINTS
```

Temperature measurements can be taken by either thermocouples or thermistors. A data acquisition system collects all temperature drop measurements almost simultaneously transferring those readings to a microcomputer in order to be processed.

After the drying is initiated, temperature drop across the load measurements are taken for all 24 positions. The highest TDAL measured is compared to a pre-set optimum value obtained by solving Equation 34 for TDAL. After comparison, the computer (refer to diagram illustrated in Figure 44) will determine a control action to be performed. If the measured TDAL is smaller than the pre-set value, the heating system for the particular zone where the TDAL was taken is activated. If the TDAL is larger no further heating is needed. After the first decision is made, all subsequent temperature drop readings (TDAL-2 to TDAL-24) are compared to the first corrected TDAL and subsequent individual control actions are performed.

For any instant of the drying process, a desired moisture content loss may be substituted into Equation 34 which then, determines the TDAL to be utilized. As the TDAL changes, the values of the physical properties involved in the model (density and specific heat capacity of the mixture air and water-vapor) may be corrected according to average temperature values within the pile. The new values for the physical properties are substituted into Equation 34 and a new TDAL is calculated according to the desired moisture content loss. With all information on TDAL, a three-dimensional graph can be constructed which then illustrates predicted drying rates and moisture content variation throughout the drying process.

The predicted drying rates obtained through Equation 34 can be substituted into Equation 38, in order to estimate the temperature of the surface of the wood and therefore to monitor its variation throughout the drying process. Knowledge of this temperature is important when assessing possible effects on mechanical properties of the lumber being dried.

As mentioned earlier, measured TDAL can be substituted into Equation 25 which can be integrated with respect to time in order to obtain information on energy usage. The estimated energy value obtained, can be utilized to compare to actual measured energy values and therefore to establish the overall performance of the equipment.

In addition to provide estimates of drying rates and moisture content throughout the drying process, the TDAL can be utilized to avoid overdrying at the lumber indicating the time when the process must be terminated because it can be related to final average moisture content. As a result, it is expected a more uniform moisture content for the entire load will result in less degrade warp caused by excessive drying.

In addition of being a control technique, the TDAL concept can also be utilized to improve current drying schedules, check drying conditions for an existing dryer, and to evaluate and propose new dryer designs.

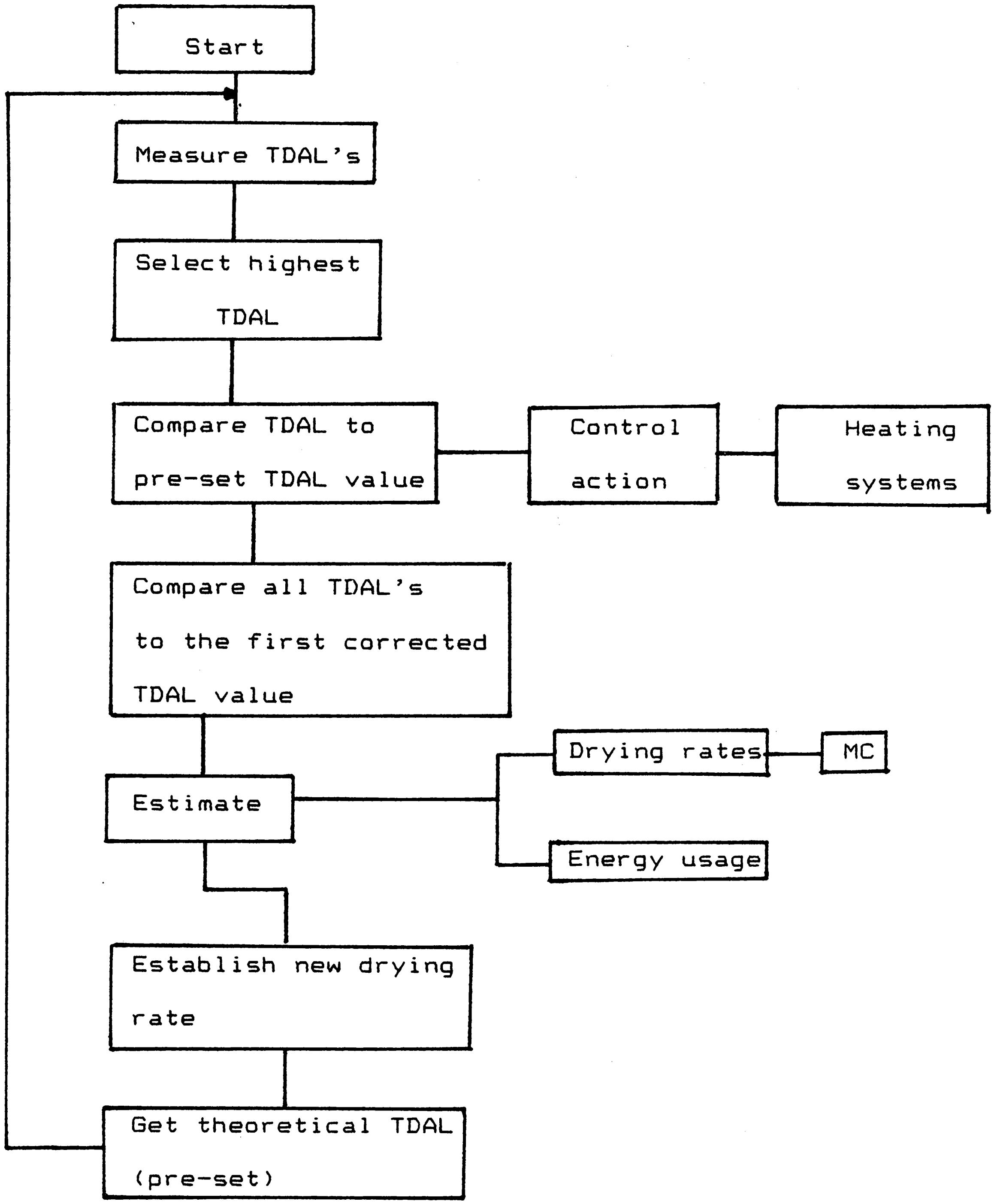

Fig.44 Control diagram.

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Appendix 1: Energy and Mass balance

As illustrated in Figure 1, unsaturated heated air approaches the wood with a constant and uniform temperature, Ta. Energy is then transferred from the air and water-vapor mixture to the wood element which is initially at an uniform temperature Tw_i. The initial moisture content of the wood is assumed equal to MC_i.

Neglecting radiation as well as small quantities of air inside the wood, the following equation can be written (Equation 24):

$$\dot{q}(t) = M_{wwd} C_{wwd} \frac{dT}{dt} + L_v d_{wd} \frac{dxdydz}{2} \frac{dMc}{dt}$$

...(Eq.A.1.1)

where:

q(t) = Rate of energy reaching the wood (Kcal/h)

m_{wwd} = Mass of wet wood (Kg)

d_{wd} = Basic density of wood (Kg/m^3)

x,y,z= Thicknesses of the wood along their axes (cm)

C_{wwd} = Specific heat capacity of wet wood (Kcal/Kg °C)

T = Temperature of the wood (°C)

t = Time (h)

L_v = Latent heat of vaporization of water (Kcal/Kg)

MC = Average wood moisture content (%)

Multiplying the first term of the second member of Equation 24 by dMC/dMC, it yields:

$$q(t) = M_{wwd}C_{wwd}\frac{dT}{dt}\frac{dMC}{dMC} + L_v d_{wd}\frac{dxdydz}{2}\frac{dMC}{dt}$$

...(Eq.A.1.2)

or

$$q(t) = M_{wwd}C_{wwd}\frac{dT}{dMC}\frac{dMC}{dt} + L_v d_{wd}\frac{dxdydz}{2}\frac{dMC}{dt}$$

...(Eq.A.1.3)

The mass of wet wood (M_{wwd}) can be expressed by:

$$M_{wwd} = d_{wd}\frac{dxdydz}{2}(1 + mc)$$ ...(Eq.A.1.4)

where:

MC = Fractional moisture content of wood (% MC/100)

Substituting Equation A.1.4 into Equation A.1.3, gives:

$$q(t) = d_{wd} \frac{dxdydz}{2} [(1 + mc) C_{wwd} \frac{dT}{dMC} + L_v] \frac{dMC}{dt}$$

...(Eq.A.1.5)

and rearranging it:

$$q(t) = d_{wd} \frac{dxdydz}{2} L_v [(1 + mc) \frac{C_{wwd}}{L_v} \frac{dT}{dMC} + 1] \frac{dMC}{dt}$$

...(Eq.A.1.6)

The dimensionless group that appeared in Equation A.1.6 $[(1 + mc)\ C_{wwd}\ dT/dmc]$ is referred as the Rebinder (Rb) number (Luikov 1967).

(Recall: The Rebinder number expresses the ratio of the energy to heat the moist wood to the energy used to evaporate water during an infinitesimally small interval of time).

For unidirectional flow Equation A.1.6 can be rewritten as:

$$q(t) = d_{wd}\ (Y/2)\ Z\ L_v \frac{dMC}{dt} (1 + Rb)\ dx$$

...(Eq.A.1.7)

This is the basic equation for the kinetics of the drying process.

In high temperature drying of wood, the overall Rb number for the process is normally very small. For example for the particular case of high temperature drying of southern yellow pine dimension lumber, the temperature of the process is usually increased from 68 °F (20 °C) up to 240 °F (115.6 °C) while the moisture content decreases from 120% to 15%. Assuming an average specific heat capacity (C_{wwd}) of 0.571 Btu/(lb °F) (0.571 Kcal/Kg °C) and an average latent heat of vaporization of 1000 Btu/lb (555 Kcal/Kg °C), the overall average Rebinder number is approximately 0.0015. This indicates that for the most part of thé drying process, the overall energy required to evaporate the water is much larger than the energy necessary to heat up the wet wood.

Appendix 2: Intensity of Mass Transfer During High Temperature Drying of Southern Yellow Pine.

Before applying Equations 35 and 36 for different drying medium conditions of humidity, it is necessary to investigate whether or not high temperature drying of southern yellow pine can be classified as a low mass transfer process. In order to approach this particular problem, the following derivation is based on the discussion of simultaneous heat and mass transfer given by Bennet and Myers (1974), and adapted for the particular case of high temperature drying of southern yellow pine.

As shown in Figure A.2.1, a stationary film of thickness "e" is assumed to exist near the surface where transference process of heat and mass are occurring. It should be pointed out that the film theory constitutes a simplified approach to the simultaneous heat and mass transfer, because it assumes that the film thickness is not affected by mass transfer (Bird et al. 1960). However, the graph (Figure 21.7-2, page 675) presented by Bird et al. (1960) indicates that the results obtained by using the film theory are close to the results obtained when using more sophisticated theories such as the

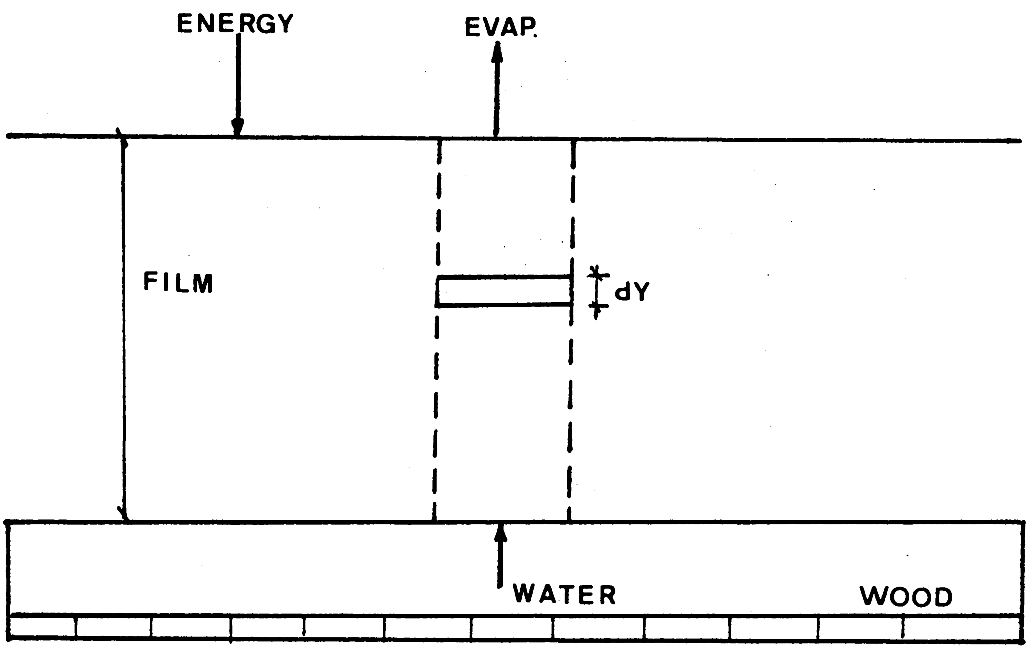

Fig.A.2.1 Hypothetical stationary film over the surface of the wood.

Penetration and Boundary Layer Theory.

The amount of energy crossing the film layer as illustrated in Figure A.2.1, reaches the wood surface where it is used to heat the moist wood and to evaporate a certain amount of water (Bennet and Myers 1974). Mathematically this can be expressed by:

$$h(Ta - Ts)dA = M_{wwd}C_{wwd} \frac{dT}{dt} + L_v \frac{dm_w}{dt} \quad \text{...(Eq.A.2.1)}$$

where:

h = Convective heat transfer which includes the energy transported through the film thickness carried by convective mass transfer due to evaporation [Kcal/(mt^2 h °C]

Ta = Air temperature outside the boundary layer (°C)

Ts = Wood surface temperature (°C)

A = Wood surface area (mt^2)

M_{wwd} = Mass of moist wood (Kg)

t = Time (h)

L_v = Latent heat of vaporization (Kcal/Kg)

dm_w/dt = Mass of water evaporated (drying rate Kg/h)

As water is removed from wood and transferred into the film layer, it carries a certain amount of energy. This energy corresponds to the enthalpy change (Ha - Hs) required to bring the water from its original state inside the wood to the vapor phase in the film thickness. Considering the energy carried by convective mass transport into the film thickness, the following expression can be written:

$$h'(Ta - Ts)dA = M_{wwd}C_{wwd}\frac{dT}{dt} + L_v\frac{dm}{dt} + (Ha - Hs)\frac{dm_w}{dt}$$

...(Eq.A.2.2)

where:

h' = Convective heat transfer coefficient for simultaneous heat and mass transfer which does not include the energy carried out by the evaporating fluid [Kcal/(mt^2 h °C)]

Assuming that all energy required for liquid evaporation is supplied by conduction through the hypothetical film layer and that temperature inside the wood in the beginning of the drying process is approximately constant, the following energy balance can be written:

$$L_v \frac{dm_w}{dt} + (Ha - Hs) \frac{dm_w}{dt} = k \frac{dT}{dy} \qquad \text{...(Eq.A.2.3)}$$

where:

k = Thermal conductivity of the air in the film layer [Kcal m/(m^2 h °C)]

y = Vertical distance in the boundary layer (cm)

According to Bennet and Myers (1974), the enthalpy difference in Equation A.2.3 can be expressed by:

$$Ha - Hs = Cp_{am} (Ta - Ts) \qquad \text{...(Eq.A.2.4)}$$

where:

Cp_{am} = Specific heat capacity of the mixture air and water-vapor (Kcal/Kg °C)

Substituting Equation A.2.4 into Equation A.2.3 and rearranging it, the following expression is obtained:

$$[L_v + Cp_{am} (Ta - Ts)] \frac{dm_w}{dt} = kA \frac{dT}{dy} \qquad \text{...(Eq.A.2.5)}$$

Assuming that after the initial heating up period, but still in the early stages of drying the overall drying rate approximates a constant value (N_w), Equation A.2.5 can be written as:

$$[L_v + Cp_{am} (Ta - Ts)] N_w = kA \frac{dT}{dy} \quad ...(Eq.A.2.6)$$

The approximate constant drying rate (N_w) can be evaluated when Equation A.2.6 is integrated according to the boundary conditions established by the film thickness, therefore:

$$N_w \int_0^e dy = kA \int_0^T \frac{dT}{L_v + Cp_{am}(Ta-Ts)} \quad ...(Eq.A.2.7)$$

Integration of Equation A.2.7 yields:

$$N_w = \frac{kA}{eCp_m} \ln [1 + \frac{Cp_m}{L_v}(Ta - Ts)] \quad ...(Eq.A.2.8)$$

As it has been assumed, the temperature variation in the initial stages of the drying process (after the heating up period) is small and therefore, Equation A.2.1 can be written as:

$$h\ (Ta - Ts)\ dA = N_w\ L_v \qquad \text{...(Eq.A.2.9)}$$

Combination of Equation A.2.8 and A.2.9 results in:

$$\frac{h(Ta - Ts)}{L_v} = \frac{k}{e\ Cp_{am}} \ln \left[1 + \frac{Cp_{am}}{L_v} (Ta - Ts)\right] \qquad \text{...(Eq.A.2.10)}$$

In absence of mass transfer, the convective heat transfer coefficient through the film layer (h") is by definition given by (Bennet and Myers 1974). Therefore h" can be expressed by:

$$h" = \frac{k}{e} \qquad \text{...(Eq.A.2.11)}$$

Therefore, substitution of Equation A.2.11 into Equation A.2.10 yields the following expression:

$$\frac{h(Ta - Ts)}{L_v} = \frac{h"}{Cp_{am}} \ln \left[1 + \frac{Cp_m}{L_v} (Ta - Ts)\right] \qquad \text{...(Eq.A.2.12)}$$

Equation A.2.12 expresses a relationship between the convective heat transfer coefficient without mass transfer (h") and the overall convective heat transfer which has incorporated to it the energy carried into the film layer by the evaporating fluid.

In Equation A.2.12 substituting

$$\frac{Cp_{am}}{L_v} (Ta - Ts) = F \qquad \text{...(Eq.A.2.13)}$$

the relationship between h and h" is:

$$\frac{h}{h''} = \frac{\ln (1 + F)}{F} \qquad \text{...(Eq.A.2.14)}$$

Taking Equation A.2.2 dT/dt = 0, it yields:

$$h' (Ta - Ts)\, dA = L_v N_w + (Ha - Hs)\, N_w \text{...(Eq.A.2.15)}$$

The enthalpy difference Ha-Hs is given by Equation A.2.4, therefore:

$$h' (Ta - Ts)\, dA = L_v N_w + Cp_{am} (Ta - Ts)\, N_w \qquad \text{...(Eq.A.2.16)}$$

and

$$h' \ (Ta - Ts) \ dA = N_w L_v \ [1 + \frac{Cp_{wm}}{L_v}(Ta - Ts)]$$ ...(Eq.A.2.17)

Substituting Equation A.2.9 into Equation A.2.17:

$$h' \ (Ta - Ts) \ dA = h \ (Ta - Ts) \ dA \ [1 + \frac{Cp_{wm}}{L_v} \ (Ta - Ts)]$$ ...(Eq.A.2.18)

therefore

$$\frac{h'}{h} = 1 + F$$ ...(Eq.A.2.19)

For practical purposes, during high temperature drying of southern yellow pine, assuming that an adequate air velocity is provided, the following are typical average values during the early stages of drying:

Cp_{wm} = 0.350 Btu/lb °F (.350 Kcal/Kg °C)

L_v = 1000 Btu/lb (555 Kcal/kg)

Ta = 240 °F (115.6 °C)

Ts = 160 °F (71.1 °C)

Substituting these values in Equations A.2.14 and A.2.19 the following ratios are obtained:

h/h" = 0.99

h/h' = 0.97

The results above indicate that in early stages of the high temperature drying process, when the highest drying rates values are normally observed, the effect of mass transfer flowing into the drying medium is small because the convective heat transfer coefficients are approximately the same. Therefore, convective high temperature drying of southern yellow pine can be considered a low mass transfer process.

As a result, the corrections factors suggested by Bird et al. (1960) do not need to be introduced in Equations 35 and 36. The results determined by the ratios between convective heat transfer coefficients support the assumption that rates of mass transfer do not affect the rate of heat transfer.

APPENDIX 3: HP-41 CV computer program for the data acquisition and control system.

```
001 LBL "INI VOL"
002 CLRG
003 "INITIALIZATION"
004 PRA
005 "ROUTINE"
006 PRA
007 ADV
008 "--------------"
009 XEQ "PRA"
010 ADV
011 XEQ "INI3421"
012 DATE
013 STO 47
014 FIX 2
015 TIME
016 HR
017 STO 48
018 STO 40
019 "DCV9"
020 OUTA
021 IND
022 100000
023 *
024 INT
025 100
026 /
027 STO 00
028 RCL
029 HMS
030 "TIME="
031 XEQ "PRINT"
032 RCL 00
033 "INI VOLT IS"
034 XEQ "PRINT"
035 "*********"
036 XEQ "PRA"
037 "NEXT NUMBER IS"
038 "LOAD BEAM CT"
039 2.058
040 STO 32
041 "TIME INT"
042 PROMPT
```

```
STO 49
"WBMAX"
PROMPT
STO 52
"WBMIN"
PROMPT
STO 53
ADV
ADV
ADV
CLOCK
END
LBL "WEIGHT"
XEQ "INI3421"
RCL 48
RCL 49
+
TIME
HR
X<>Y
X>Y?
GTO "WB-1"
X<>Y
STO 48
"NEXT IS CTR"
1
ST+ 45
TIME
HR
STO 50
"DCV9"
OUTA
IND
100000
*
INT
100
/
STO 01
RCL 50
HMS
FIX 2
"TIME="
XEQ "PRINT"
FIX 4
RCL 01
RCL 00
-
```

```
091 ABS
092 RCL 32
093 /
094 STO 33
095 DATE
096 STO 46
097 RCL 47
098 X>Y?
099 GTO "MIDNITE"
100 RCL 50
101 RCL 40
102 -
103 STO 34
104 HMS
105 "ELAPSED TIME="
106 XEQ "PRINT"
107 LBL "WATER"
108 RCL 33
109 "WEIGHT LOSS="
110 XEQ "PRINT"
111 ADV
112 ADV
113 TEMPERATURES
114 XEQ "PRA"
115 ADV
116 "TEM2-8"
117 OUTA
118 IND
119 STO 02
120 ST+ 03
121 IND
122 STO 04
123 ST+ 05
124 IND
125 STO 06
126 ST+ 07
127 IND
128 STO 08
129 ST+ 09
130 IND
131 STO 10
132 ST+ 11
133 IND
134 STO 12
135 ST+ 13
136 IND
137 STO 14
138 ST+ 15
```

```
139  "EVAL TDAL"
140  RCL 02
141  RCL 04
142  -
143  ABS
144  STO 16
145  ST+ 17
146  "EVAL. TDAL-2"
147  RCL 12
148  RCL 02
149  -
150  ABS
151  STO 18
152  ST+ 19
153  "EVAL. TDAL-3"
154  RCL 04
155  RCL 12
156  -
157  ABS
158  STO 20
159  ST+ 21
160  "EVAL H FL"
161  RCL 02
162  RCL 06
163  -
164  STO 22
165  ST+ 23
166  RCL 12
167  RCL 08
168  -
169  STO 24
170  ST+ 25
171  RCL 04
172  RCL 10
173  -
174  STO 26
175  ST+ 27
176  "WBD"
177  RCL 02
178  RCL 14
179  -
180  STO 28
181  ST+ 29
182  FIX 1
183  RCL 02
184  T-INCIMING AIR=
185  XEQ "PRINT"
186  RCL 04
```

```
T-LEAVING AIR=
XEQ "PRINT"
ADV
RCL 16
"TDAL="
XEQ "PRINT"
RCL 18
"TDAL-2="
XEQ "PRINT"
RCL 20
"TDAL-3="
XEQ "PRINT"
ADV
RCL 06
"SFC T-1="
XEQ "PRINT"
RCL 08
"SFC T-2="
XEQ "PRINT"
RCL 10
"SFC T-3="
XEQ "PRINT"
RCL 12
T-AIR MIDDLE=
XEQ "PRINT"
ADV
RCL 14
"WBT="
XEQ "PRINT"
RCL 28
"WBD="
XEQ "PRINT"
RCL 12
RCL 14
-
STO 30
ST+31
"WDB-2="
XEQ "PRINT"
RCL 04
RCL 14
-
STO 35
ST+ 36
"WBD-3="
XEQ "PRINT"
RCL 22
ADV
```

```
235  "H FL-1="
236  XEQ "PRINT"
237  RCL 24
238  "H FL-2="
239  XEQ "PRINT"
240  RCL 26
241  "H FL-3="
242  XEQ "PRINT"
243  ADV
244  RCL 02
245  RCL 12
246  +
247  RCL 04
248  +
249  3
250  /
251  STO 37
252  ST+ 38
253  "AVG T PILE="
254  XEQ "PRINT"
255  RCL 06
256  RCL 08
257  +
258  RCL 10
259  +
260  3
261  /
262  STO 43
263  ST+ 44
264  "AV SFC T="
265  XEQ "PRINT"
266  ADV
267  ADV
268  "SUMMARY"
269  PRA
270  FIX 4
271  ADV
272  RCL 34
273  HMS
274  "ELAPSED TIME"
275  XEQ "PRINT"
276  RCL 39
277  RCL 33
278  -
279  ABS
280  RCL 50
281  RCL 41
282  -
```

```
283  /
284  ST+ 42
285  FIX 2
286  "DRYING RATE="
287  XEQ "PRINT"
288  RCL 42
289  RCL 45
290  /
291  "AVG DRY RATE="
292  XEQ "PRINT"
293  RCL 03
294  RCL 45
295  /
296  FIX 1
297  "AVG IN TEMP="
298  XEQ "PRINT"
299  RCL 05
300  RCL 45
301  /
302  "AVG LEAV. T="
303  XEQ "PRINT"
304  RCL 17
305  RCL 45
306  /
307  "AVG TDAL="
308  XEQ "PRINT"
309  RCL 19
310  RCL 45
311  /
312  "AVG TDAL-2="
313  XEQ "PRINT"
314  RCL 21
315  RCL 45
316  /
317  "AVG TDAL-3="
318  XEQ "PRINT"
319  RCL 23
320  RCL 45
321  /
322  "H. FLUX-1="
323  XEQ "PRINT"
324  RCL 25
325  RCL 45
326  /
327  H. FLUX-2="
328  XEQ "PRINT"
329  RCL 27
330  RCL 45
```

```
331 /
332 "H. FLUX-3="
333 XEQ "PRINT"
334 RCL 38
335 RCL 45
336 /
337 "AVG TEMP PILE="
338 XEQ "PRINT"
339 RCL 44
340 RCL 45
341 /
342 "AVG SFC T="
343 XEQ "PRINT"
344 RCL 07
345 RCL 45
346 /
347 "AVG T SFC-1="
348 XEQ "PRINT"
349 RCL 09
350 RCL 45
351 /
352 "AVG T SFC-2="
353 XEQ "PRINT"
354 RCL 11
355 RCL 45
356 /
357 "AVG T SFC-3"
358 XEQ "PRINT"
359 RCL 15
360 RCL 45
361 /
362 "AVG WET BULB="
363 XEQ "PRINT"
364 RCL 29
365 RCL 45
366 /
367 "AVG WBD="
368 XEQ "PRINT"
369 RCL 31
370 RCL 45
371 /
372 "AVG WBD-2="
373 XEQ "PRINT"
374 RCL 36
375 RCL 45
376 /
377 "AVG WBD-3="
378 XEQ "PRINT"
```

```
ADV
"************"
XEQ "PRA"
ADV
ADV
ADV
ADV
RCL 33
STO 39
RCL 50
STO 41
GTO "WB-1"
LBL "C-1"
CLOCK
END
LBL "INI3421"
AUTOIO
CF 17
"HP3421A"
FINDID
SELECT
RTN
END
LBL "MIDNITE"
RCL 50
RCL 40
+
STO 34
HMS
"ELAPSED TIME"
XEQ "PRINT"
GTO "WATER"
END
LBL "WB-1"
"TEM8"
OUTA
IND
STO 51
RCL 53
X<>Y
X>Y?
GTO "WB-2"
"CLS00"
OUTA
GTO "C-1"
END
LBL "WB-2"
RCL 52
```

```
RCL 51
X>Y?
"OPNOO"
OUTA
GTO "C-1"
END
LBL "PRINT"
XEQ "FMT"
XEQ "ACA"
XEQ "ACX"
XEQ "PRBUF"
RTN
END
LBL "TEST"
"DCV9"
OUTA
IND
PRX
END
```

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