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Title : Application of Hart's Computer Simulation to the Drying of 2-inch Thick Douglas-fir Heartwood Lumber

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The purpose of this study was to compare the drying curves of 2-inch thick Douglas-fir heartwood boards as predicted by a computer simulation by C. A. Hart (1983) with those actually observed in experimental kiln runs. The moisture gradients within test boards were also simulated by the computer program and actually monitored by a thermo-moisture meter constructed by J. Forrer (1984). The measurements of moisture gradients in single boards and across a stack of boards were made in a small experimental kiln and in an industrial kiln respectively using a common kiln schedule.

In spite of correctable temperature effects on the monitored D.C. resistance values, Forrer's thermo-moisture meter performed well in the determination of moisture changes in different depths of test boards and in reflecting warm-up time and maximum moisture gradients.

Moisture gradients in single boards or between boards in a stack, as predicted by the simulation program, came close to observed values. After adjustments of computer inputs, the simulated drying curves came into very good agreement with the actual drying curves. The same was true for moisture gradients predicted by the simulation and monitored by the thermo-moisture meter. Thus, Hart's computer simulation originally developed for and verified on white oak lumber worked for the drying of Douglas-fir heartwood lumber as well.

Both the simulation program and the thermo-moisture meter appear to be excellent tools for studying the drying behavior of wood.

Application of Hart's Computer Simulation to the Drying of 2-inch Thick Douglas-fir Heartwood Lumber

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INTRODUCTION

The goal of kiln drying of lumber is to reduce its moisture as quickly as possible with minimum of drying defects. During drying, when wood starts to shrink, it is subject to stresses which may cause drying defects such as surface and internal checks. These stresses develop because the outside of green lumber dries below the fiber saturation point and starts to shrink before the interior is ready for shrinkage. Because moisture gradients developing during the drying of lumber are the very cause of drying stresses, drying conditions must be controlled. If moisture gradients in boards can be predicted during drying, kiln schedule might be designed which prevent drying defects. Eventually, profit will be gained by preventing lumber degradation as well as reducing energy consumption in kiln drying by using optimum drying schedules.

A lumber drying simulation program developed by C. A. Hart (1983) uses as input the drying rates of boards and their average moisture contents to predict moisture gradients not only within a board, but also between boards within a stack. Hart verified his simulation with drying data of 1-inch thick white oak lumber. Once the simulation obtains a good fit to actual drying data, any chosen drying parameter can be varied and the simulation will show the effect of these changes on the drying rate. Therefore, kiln operators and research scientists might be able to use drying simulations for the modification of drying schedules.

A moisture monitoring device constructed by J. Forrer (1984) was designed to continuously measure moisture gradients in a board or between boards during drying. It is a resistance type moisture meter using alternating current and controlled by a microprocessor. Its probes have been developed to be buried in wood to measure the moisture contents at various depths.

OBJECTIVE

The purpose of this project was to compare the drying curve of 2-inch thick Douglas-fir heartwood boards to be predicted by C. A. Hart's computer simulation with that actually observed in experimental kiln runs. The change in moisture gradients within test boards was to be assessed by means of the moisture monitoring system newly designed by J. Forrer.

LITERATURE REVIEW

Drying Stresses and Moisture Gradients

When a piece of freshly cut wood is exposed to a drying condition, its surface starts to dry first. When any portion of wood loses moisture below the fiber saturation point (FSP), it starts to shrink (Stamm, 1964). If this shrinkage takes place before the interior of this piece is ready for shrinkage, stresses develop. McMillen (1958) demonstrated their magnitude by experimentation and quantified the stress-strain relationship. Strain produced by short-time stress below the proportional limit substantially disappears when the load is released. Such strain is called the elastic strain. Stress beyond the proportional limit, or stress below the proportional limit applied for long periods of time, produces some strain which does not disappear upon release of the load. This permanent strain is called set. Usually, drying gradients are steep enough to cause stresses to exceed the proportional limit of wood in tension or compression and cause set. Knight (1933) expressed the opinion that drying stresses are absolutely unavoidable and sets apparently are, too.

McMillen (1958) showed typical drying stresses and moisture gradients at different stages of drying of 2 -inch thick red oak heartwood using a slicing method, while Espenas (1952) reported that softwood, notably Douglas-fir, did not develop the same stress patterns as most hardwoods. He expressed his opinion that tensile stresses that produce surface checking persist long into the drying cycles. During the middle and final stages of drying, higher relative humidity (RH) is required than in drying hardwoods. Finally a reversal of stresses develops and humidity control is no longer as critical.

Surface and end checking, splitting, collapse, honeycombing, and severe case-hardening are all directly connected with excessive drying stresses. If the drying conditions can be manipulated to cause set in proper amount, yet not cause drying defects, stress will be reduced sooner and drying can be accelerated without danger of the mentioned defects. As mentioned before, stresses are directly related to moisture gradients. Also the strength to proportional limit, the maximum strength, and the stress-strain ratio are all influenced by moisture content (MC). Shrinkage is also inversely proportional to MC below the FSP. Roth (1895) already recognized some connections between case-hardening and checking. Tiemann (1917), however, was probably the first to understand stresses and set in wood and to make prong tests for stress analyses. Youngs and Norris (1958) calculated drying stresses, including shear, at various points throughout the cross section of boards using perpendicular to grain mechanical properties determined earlier (Youngs, 1957). McMillen (1955) showed that information on the MC of the slices at various drying stages should be of primary interest in interpreting the shrinkage, strain, and set data. Hart (1965) studied the nature of moisture gradients in drying wood, the variables which affect these gradients, and the net result upon drying time. He suggested that the rate of moisture diffusion below fiber saturation was directly proportional to the MC gradient for a given range of MC. Thus, the steeper the moisture gradient from the wood surface to the interior, the faster the drying.

Using knowledge of drying stresses and moisture gradients in drying wood, many investigators have devoted time to improving kiln drying schedules. Rietz (1950) and McMillen (1952) described basic principles of lumber drying and how they could be used in developing a new concept of kiln scheduling. In 1951, Torgeson published a whole new series of kiln schedules for American woods based on these principles. Now, initial drying conditions can be set up that will avoid surface and end checks, retain maximum lumber dimensions, and minimize warping. Intermediate and final kiln conditions can be modified to speed drying without fear of internal defects. Final conditioning treatments can be used when necessary to relieve residual stresses at the end of kiln drying, thus avoiding distortion when material is resawed or machined to a nonsymmetrical pattern.

Electrical Moisture Meters

Most of the important properties of wood are influenced considerably by MC, which is subjected to wide variation depending on its environment and history. For this reason, many workers have searched for efficient and reliable methods of measuring wood moisture. Since MC is defined as the fraction of the weight of the water contained in the wood to its oven-dry weight it can be measured absolutely by mass. The oven drying method is, in general, the most precise moisture measurement method, however, it is not accurate for some species that contain large amounts of volatile materials other than water. Therefore, James (1963) suggested the distillation method by which the amount of water removed from a specimen can be measured directly.

These two basic methods of measuring wood moisture have disadvantages. For instance, if the determination of moisture gradients is required, the oven dry mass can be known accurately only after the experimental run (Forrer, 1984). Thus, all calculation for MC would be retrospective. The moisture gradients in wood cannot be determined without destruction of wood, thus, these methods are not suitable for real-time measurements (Hildebrand, 1970).

Some electrical properties of wood ,described below, can be used for measuring its moisture content. Presently, three types of electric moisture meters have been developed and are on the market. Each is based on a different fundamental relationship (James, 1963): 1)the radio-frequency power loss type, which uses the relationship between MC and the dielectric loss factor of the wood; 2) the capacitance type, which uses the relationship between MC and the dielectric constant of the wood; 3) the resistance type, which uses the relationship between MC and direct current resistance. James (1968) also examined the effect of temperature on readings of these three meter types.

The dielectric constant of a material is defined as the ratio of the capacitance of a capacitor using a material as the dielectric to the capacitance of the same capacitor with a vacuum (or practically, dry air) as the dielectric. In principle, the dielectric constant is a measure of how much electric potential energy is stored in the material when it is placed in a given electric field (James, 1963). The dielectric constant of most dry cellulosic materials falls in the range of 1.5 to 30 (Stamm, 1965). As the moisture content increases from 0% to about 30%, the dielectric constant of wood increases along a curve that is concave upward (Skaar, 1948). Above 30% MC, the dielectric constant increases roughly linearly with an increase in moisture. The dielectric constant of wood decreases as the frequency increases over a range of 2 and 15 megacycles. In addition to moisture and frequency, wood density also influences the dielectric constant. Peterson (1960) investigated the relationship of wood density to dielectric constant with 10 species and concluded that for wood in the oven dry state there was a strong linear relationship between them, but for other MC the relationship takes the form of an exponential curve, the slope of the curve increasing with density.

When wood is placed in a constant alternating electric field, it absorbs a certain amount of energy from the field and a portion of it is dissipated in the form of heat (Brown, 1952); the heat results from friction between the molecules of wood substance and from friction within the individual molecules. The power factor of a dielectric material is the ratio of the electric energy dissipated per cycle of oscillation in condenser to the total electrical energy stored in the condenser during the cycle. Since the energy stored is proportional to the dielectric constant, the energy loss per cycle is proportional to the product of the power factor and the dielectric constant. This latter product is the dielectric loss factor. The loss factor also varies with MC. But the interaction effect of temperature and MC on the loss factor is not a simple relationship. From his experiments, James (1968) found that the loss factor went through maximum and minimum values as the temperature varied at a given MC. It also has a slight correlation to the density of wood (Peterson, 1960) however, this relation is not as marked as that between dielectric constant and density. Dielectric behavior of wood has practical significance in determining wood MC. However, even prototype meters that used the apparently ideal design do not demonstrate the expected advantages over commercial meters (James,1981). Furthermore, Mackay (1976) pointed out that the presence of a moisture gradient caused the power loss meter to read incorrectly. He concluded that the effective penetration of the power loss meter was not more than one-tenth of an inch.

Since Stamm (1927) pointed out the usefulness of the electric resistance of wood as a means of measuring its MC, the electric conductivity of wood has been studied by a number of wood technologists. Clark and Williams (1933) suggested, and Davidson (1958) confirmed that electrical conductivity of wood was an ionic process rather than an electronic one as in metals. Two forms of ions are present in the wood structure: bound ions whose number is dependent upon the temperature, and free ions, the only ions able to conduct a charge. Accordingly, the dependency of the electric resistance of wood on temperature can be explained by the theory that the number of bound ions is dependent upon temperature.

The electrical resistance of wood is strongly influenced by its MC. James (1963) found that a rough linear relationship existed between the logarithm of the electric resistance and the inverse of the logarithm of the MC in the MC range from the fiber saturation point to the oven dry condition. For resistance type moisture meters, MC is derived from empirical formulas (Keylwerth and Noack, 1956). For his experiments, Forrer (1984) used the following formula which had been devised by Siemens and Halle (Keylwerth and Noack, 1956).

$$\log(\log(r)-4) = -0.0322\ U + 1.009 \quad \text{[1]}$$

where r = specific resistance(ohm-cm) and
U = MC(%)

This formula gives a good agreement with James' experimental data (1963) about the relationship of electric resistance to MC for Douglas-fir (Appendix A).

However, Skaar (1964) examined several factors which made it difficult to directly measure MC of wood by its electrical resistance. Among these factors are: temperature; polarization phenomena, which cause resistance to change with time; voltage gradients; and the concentration of resistance in the vicinity of the electrodes due to electrode geometry, poor contact, and the accumulation of electrode deposits.

A number of workers (Skaar, 1948; Davidson, 1958; Brown et al., 1952), investigating the electric resistance of wood as affected by temperature, have shown that there is some relationship between the logarithm of electrical resistivity and the reciprocal of absolute temperature. Lin (1965) showed this relationship in detail. He studied the relationship between log r (electrical resistivity) and 1/T (absolute temperature) at temperature ranges from -60 °C to +165 °C and showed the curvilinearity of their relations at high MC.

In studying the direct current electrical properties of wood, factors other than MC and temperature must be considered. Murphy (1929) used cotton as a cellulosic material and found that as the voltage decreased the resistance increased. On the other hand, Skaar (1964) showed that for direct current above 10 V, resistivity measurements are practically independent of the applied voltage. Another effect to be considered is the complex nature of electrical conductivity in hygroscopic dielectrics. Murphy and Morgan (1937) pointed out that, when a static electric field is applied to a dielectric, a current flows only for a certain length of time. The time of current flow is that required for the particles in the material to reach a fully polarized condition. Practically, normal materials are not completely polarized, which would be the case for an ideal material. Since the degree of polarization is dependent upon the length of time the electric field is applied and direct current produces ionic heating (Lin, 1965), a lengthy charge will influence the apparent MC. It is generally accepted that this kind of polarization is due to the local accumulation of electrolyte products within the cell wall (Brown, 1963; Skaar, 1964), so polarization is usually most pronounced when wood MC is high. Therefore, to avoid these disadvantages, Forrer (1984) used low frequency alternating current in constructing his temperature and moisture monitoring device which was used for this research.

Electrode geometry is defined by pin size and spacing, and can influence the immediate force fields of the electrodes. The linear spacing of small diameter pins is less critical for resistivity measurements (Skaar, 1964) because the bulk of resistance is concentrated in the immediate vicinity of the electrodes. In addition to the above electric properties of wood, Venkateswaren (1974) found a linear relationship between the lignin content and D.C.-conductivity of vacuum dried wood. This study showed that electrical measurements could be used as a nondestructive analytical tool for estimating lignin content in woods.

Among the many moisture measuring methods, measuring resistance is the only workable method available for monitoring real time MC gradients according to Forrer (1984). The resistance method presents a predictable relationship with MC changes that is more consistent than the dielectric method.

Lumber Drying Simulation

Some investigators of wood-moisture relations have recognized that the construction of a comprehensive mathematical model of lumber drying would provide an indication of how complete our knowledge of drying actually is. The wide and increasing use of computers also stimulates the research on theoretical predictions of drying wood.

Several attempts have been made to construct a mathematical model to simulate the drying process, at least in part. Moschler and Martin (1968) provided a simple diffusion model based on Fick's second diffusion equation. Claxton (1966) made a simple model combining the effects of permeability based on Fick's second diffusion equation, and evaporation caused by the vapor pressure differential between a wood surface and the surrounding air. Kawai et al. (1978) derived a similar diffusion model as Moschler and Martin's using the chemical potential as the driving force of moisture diffusion. Hart (1977) combined Fick's diffusion equation and evaporation parameters in a model to predict wood moisture profiles.

Two relatively complete simulation programs which may cover most transfer processes, encountered in the drying of lumber, have been developed: one by Bramhall (1979) and another by Hart (1983). Some differences exist between these two simulation programs. Hart assumed that all moisture movement within wood, even above FSP, was driven by diffusion. This is partly due to the fact that he used white oak, a refractory species, for his experiments. In contrast, Bramhall used Alpine fir, a rather fast drying species, and considered the vapor pressure gradient as the driving force in Fick's diffusion equation.

Bramhall (1979) developed a theoretical model to describe the various processes involved in moisture movement in wood that used appropriate equations with parameters. The processes are: 1) heat transfer through the boundary layer in response to a temperature differential; 2)heat conduction in wood in accordance with Fourier's equations; 3) bound-water diffusion in response to a vapor pressure gradient; 4) capillary flow in response to net surface tension forces determined by the free water differential; 5) evaporation from the wood surface due to a vapor pressure differential between a wood surface and the kiln atmosphere; and 6) the transfer of latent heat (activation energy) by diffusion and evaporation of molecules within wood.

Because the research reported here used Hart's simulation programs to compare the predicted and the observed moisture distribution in wood during drying, it is important to detail the theoretical models included in his simulations. Among them are KILDIF, KILSOR, and KILDRY: KILDIF determines the diffusion coefficients at various MCs.; KILSOR is an altered version of the published SIMSOR (Hart, 1981) and calculates the drying behavior of a single moisture profile from the surface to the center of a board; and KILDRY applies KILSOR to a stack of lumber and determines the drying rates across the stack.

1) Surface transfer

Heat and vapor transfer occurs on the wood surface because of temperature and vapor pressure differentials between the air and the wood surface. This surface transfer coefficient can be defined as the maximum possible drying rate divided by the wet bulb depression. Thus, it depends on the property of the air stream rather than that of the wood itself (Hart, 1981). Stevens et al. (1956) developed an equation as a function of air velocity:

$$\underset{(g\ cm^{-2}\ days^{-1}\ F^{-1})}{\text{Surface transfer coefficient}} = 0.0218 + 0.000092\ V \quad \ldots[2]$$

at 122.4 °F

while, McNamara (1969) gave the following equation

$$\underset{(g\ cm^{-2}\ days^{-1}\ F^{-1})}{\text{surface transfer coefficient}} = 0.0119 + 0.000138\ V \quad \ldots\ldots[3]$$

at 94.8 °F

where V = air velocity in ft/min.

2) Prediction for EMC

Accurate prediction of the EMC of wood at a given RH and temperature is important in controlling the quality of wood products. A table of EMC-RH relationships is available (Rasmussen, 1961). For easy interpolation, Smith (1963) graphed this table. Simpson (1971) applied the Hailwood and Horrobin (1946) sorption theory to the wood-water system and found three equations for its parameters. Simpson (1973) also evaluated a number of moisture sorption theories published so far with the sorption data listed in Table 38 of the WOOD HANDBOOK by the U.S. Forest Products Laboratory (1955). Sorption theories involved in his analysis are: 1) Hailwood and Horrobin 2) BET theory; 3) BET theory plus a term to approximate the effect of capillary condensation; 4) Malmquist; 5) Freundlich; 6) Bradley; 7) King ;8) Anderson and McCarthy; and 9)Pierce. Among these theories, he concluded that the 3 parameter form of the Hailwood and Horrobin theory (1946) and the King theory (1960) were the most accurate with residual sum of squares of 7.9 and 6.8 respectively, and the same average deviation of 0.1% MC.

In searching for an isotherm to fit the high moisture levels for never dried refractory hardwood, Kelly and Hart (1970) evaluated the equation

$$EMC = j\,(-\ln(1-Rw))^{k} \quad \text{[4]}$$

where EMC : equilibrium moisture content (%)
Rw : the relative vapor pressure at wood surface
j and k : parameters.

It has been found to give a good fit, although not as good as the three parameter Hailwood and Horrobin equation, when applied to EMC data (Hart, 1977). Since this formula is a two parameter equation that is easily fitted to the two EMC-relative vapor pressure points, it is ideally suited for the surface MC calculation.

If the effective surface MCs of wood at various drying stages are known the moisture distribution in wood can be predicted by the differential equation of Newmann and Richtmeyer (Moschler and Martin, 1968). As mentioned before, Hart (1977) developed mathematical models to calculate the surface MC of wood by modifying the psychrometric equation to read:

$$Rw = (Pwb - BA\ (\ Tw - Twb\ ))\ /\ PW \ \ldots\ldots\ldots\ldots\ldots [5]$$

where Rw : relative vapor pressure at wood surface
Pwb: saturated vapor pressure at wet bulb temperature (psi)
BA : psychrometric constant
Tw : wood surface temperature (F)
Twb: wet bulb temperature (F)
Pw : saturated vapor pressure at wood surface temperature (psi)

Pwb, BA, Twb are already known. If the wood surface temperature is known Rw can be computed. Once Rw is obtained, wood surface MC is easily found from the EMC isotherm. Wood surface temperature can be calculated letting total heat transfer, the difference between dry bulb temperature and wood surface temperature, be equal to the heat of sorption consumed for evaporation.

3) Calculation of diffusion coefficients

Fick's diffusion laws have been used by several investigators to describe the moisture movement in wood at MCs below the FSP. Stamm (1960) measured the diffusion coefficient of Sitka spruce in the tangential direction and calculated the diffusion coefficient from the equation based on the Boltzmann form of Fick's second law. Comstock (1963) measured the diffusion coefficient of yellow poplar in the radial direction by both the adsorption and desorption methods based on the Boltzmann solution.

McNamara and Hart (1971) used a parallel sided slab solution by Crank (1956) to obtain a diffusion equation. The complex solution for this equation is a series expansion that requires a number of terms in the early stages of sorption (Crank, 1956). However, both researchers showed that the first term of this equation gives a good approximation of the total moisture that is to be gained or lost by a sample (McNamara and Hart, 1971).

$$D = \frac{4\,a^2}{\pi^2 t} \left[\ln \frac{8}{\pi^2} - \ln(1-E) \right] \qquad [6]$$

where D = diffusion coefficient (cm/ sec)
a = half-thickness (cm)
t = time (sec)
E = the fraction amount of moisture gained or lost by the sample

The assumptions used in driving this equation are: 1) Fick's law is valid.; 2) the diffusion occurs normal to the plane of the surface.; 3) dimensional changes do not occur.; 4) moisture is initially distributed evenly throughout the specimen.; 5) the surface of the sample immediately attains equilibrium with the surroundings. McNamara and Hart (1971) also used the Boltzmann solution, called the infinite slab solution (Crank, 1956). Since it was derived for a slab of material that is infinitely thick, they pointed out that it was applicable to a slab of finite thickness as long as the moisture change at the specimen center was not large. This equation is:

$$D = \frac{\pi \ a^2 \ E^2}{4 \ t} \qquad \text{.....................[7]}$$

using the same symbols as before.

Equation [7] can be accurately applied to a finite slab from the time diffusion starts in a sample until one-half of the total moisture sorption has occurred. This is the interval of $0 < E < 0.5$.

MATERIAL AND PROCEDURE

The heartwood of Douglas-fir (Pseudotsuga menziesii), a common commercial species in the Northwest, was chosen for this study because its average fresh MC of 37% (FPL, 1974) is close to the effective maximum moisture value of 30% that can be read accurately with a resistance type moisture meter. Twelve nominally 8-foot long, 6-inch wide, and 2-inch thick freshly cut Douglas-fir heartwood boards were obtained from a sawmill in the coast range of Oregon. They were picked up on the green chain. Though the nominal thickness was 2 inches, the actual thicknesses varied from 1-1/2 inches to 1-7/8 inches and averaged 1-3/4 inches. After storage for one week in a cold room (35 °C), each 8-foot long board was cut into matched 45-inch long samples and they were end-coated with rubber-base paint immediately to prevent end drying effects. Initial MC was computed by oven-drying a 1-inch thick moisture section taken from the middle of each 8-foot long board. One of a matched pair was used to measure MC by weighing and another to, later on, examine drying stress patterns by the prong test.

Measuring Moisture Gradients in a Board

In order to monitor moisture gradients, one MC sample per kiln run was specially chosen and two 4.8 mm diameter holes were drilled to a depth of 25.5 mm equal to the length of probes. The spacing between two holes was 60 mm. It had been computed by multiplying the diameter of the electrodes (4.8 mm) by 12.5 to give a resistance to resistivity ratio of 1.0 according to the Fig. 1 (Skaar, 1964). The applied MC conversion formula (Eq. 1) requires specific resistance (or called resistivity) instead of electric resistance which is measured by Forrer's thermal-moisture meter. Fig 1 shows that when the ratio of a spacing between two electrodes to their diameter is equal to 12.5, the electric resistance value can be directly used as the specific resistance.

The probes (Fig. 2) were constructed of a ceramic tube and four stainless steel rings which were sensors for both temperature and electric resistance. Four pairs of copper-constantan thermocouple wires ran through the ceramic tube and were soldered to 4 rings respectively.

The probes were driven into predrilled holes in a sample board until the center of the top rings reached 6 mm below its surface. The thermocouple leads were soldered to the thermocouple wires from the thermo-moisture meter. Through an interface connector, the thermo-moisture meter was connected to an HP-9825 microcomputer, whose software managed four operations (Forrer, 1984): 1) measuring an isothermal temperature; 2) scanning eight themocouples; 3) controlling the charge-discharge voltages; and 4) scanning four pairs of resistance electrodes. Every 0.175 hours, the computer recorded temperatures and electric resistances of 4 selected layers in a monitored board.

Before each kiln run, twelve pairs of matched boards (Fig. 3), were stacked in a small (48 by 48 by 50 inch) experimental kiln and the rest of the kiln was filled with freshly cut Douglas-

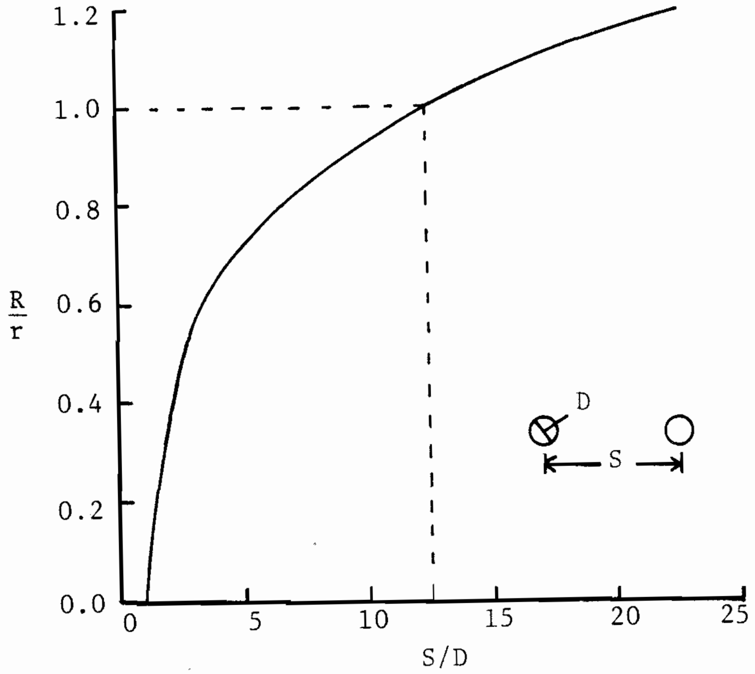

Fig. 1. Resistance-resistivity ratio R/r as a function of the spacing-diameter ratio S/D of the electrodes (adapted from Skaar 1964).

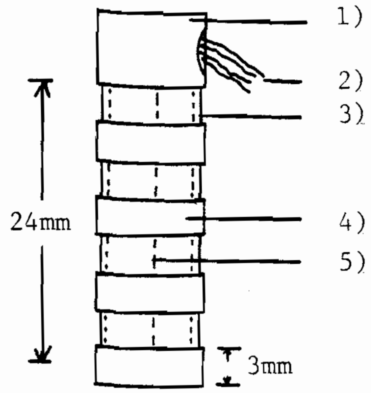

Fig. 2. Diagram of electrode for the thermo-moisture meter: 1) metal cap, 2) thermocouples, 3) ceramic tube, 4) stainless steel ring, 5) cavity for wires.

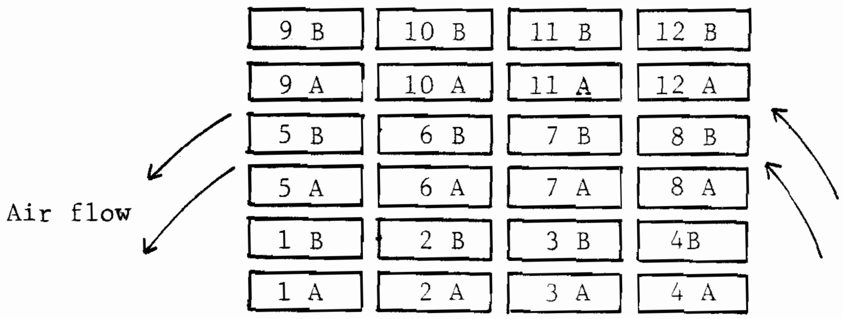

Fig. 3. Front view of stacked sample boards in the small kiln. A designates moisture sample boards and B stress test boards. Sample 9A is the monitoring sample board.

fir sapwood boards, which made it easy to obtain a humid atmosphere, especially, at the first stage of drying. Each pair of the matched boards was placed in the same location in the kiln to expose it to the same drying condition. To prevent damage to wires, the monitored board was placed at the left edge of its layer.

The drying schedule employed was one currently used in a local industrial kiln where a part of this study was to be conducted. It consisted of 7 steps with the dry bulb temperature increasing from 150°F by 5°F every 12 hours and a constant wet bulb temperature of 140°F (Table 1).

Every 12 hours, MC sample boards were weighed and a 1-inch wide cross section was sawed from each stress sample board to visually determine the stress pattern developed during the previous time interval. The stress specimens were taken about 4 inches from the end of the stress sample boards and all freshly exposed board ends were end-coated to eliminate end drying effects. Each stress specimen was made into prongs by removing a center portion. The reaction of the outer prongs was examined immediately after cutting and again after 30 minutes of exposure to ambient conditions in the Laboratory. This appeared important for slowly reacting specimens.

After 84 hours of kiln drying, the last condition of °180 F dry bulb temperature and 140°F wet bulb temperature was maintained for about 3 more days to dry the boards as close as possible to the EMC of kiln conditions. This EMC value is an important parameter

Table 1. The drying schedule used in both the experimental and the industrial kiln.

Dry-bulb temp. (°F)	Wet-bulb temp. (°F)	time (hr)
150	140	12
155	140	12
160	140	12
165	140	12
170	140	12
175	140	12
180	140	12
	Total	84

in the KILDIF and KILSOR simulation programs. Although the boards can hardly reach full equilibrium, the actual EMC of the last drying step can be estimated by extrapolating the drying rate versus MC plot to zero drying rate.

At the end of the kiln run, MC sample boards were weighed immediately and again after cooling down overnight. Then three well-spaced 1-inch thick moisture sections were taken from each moisture sample board. Based on the MC values obtained from them, the MCs at each stage were computed retrospectively.

A repetition of the kiln run was performed with a second charge of freshly cut boards averaging 1-7/8 inches in thickness. During the second kiln run, an unplanned shut down at 15 hrs occurred during the second step. Drying was restored after 3 days. However, it may have caused a reduction in the moisture gradients in boards.

Preparing Input Data of KILDIF and KILSOR for Simulating Moisture Gradients in a Board

The KILDIF and the KILSOR simulations were run on a CDC-Cyber computer for two different sets of drying rate data from each kiln charge: the average drying rate of the whole stack and the drying rate of the monitored board. The input data for KILDIF, which compute diffusion coefficients at specially selected MC levels, are shown in Table 2. The KILDIF program also provides a print-out of these input data. The output of KILDIF also provides the input data for KILSOR. This KILSOR input (Table 3) is similar

Table 2. Print-out of the initial input data to the KILDIF simulation using average moisture contents of each step in kiln Run 1.

```
      ID             DESCR(I)
       1 KILDIF. UM.DATA DOUGLAS-FIR     1984        JUNE          T=HR
     STT         WID         NPAS      IRFLOW      FANTIM      FANTST
    (IN)        (FT)          ()          ()         (T)         (T)
   .5900      2.0000           1           1    0.             .1000E+11
      SG           A           N          TW       TWDLT         TDL      NRUNMX
      ()        (CM)          ()         (F)         (F)       (%MC)          ()
  .44000     2.22000          30    80.00000     5.00000   500.00000           1
     DZT         TZD         RAE
(CM2/T)          (F)          ()
0.            0.00000      .65000
------FZ--------CZ  ------FZ--------CZ  ------FZ--------CZ
      ()     (%MC)          ()     (%MC)          ()     (%MC)
  1.0000    5.1800      1.0000    9.0000       .5000   13.1400
   .3000   17.9400      1.0000   24.8000      0.0000    0.0000
--RILRAT-------CZR  --RILRAT-------CZR  --RILRAT-------CZR
 (%MC/T)     (%MC)     (%MC/T)     (%MC)     (%MC/T)     (%MC)
-.100E-20   5.1800  -.811E-01     9.0000  -.141E+00    11.3500
-.158E+00  13.1400  -.210E+00    15.3400  -.223E+00    17.9400
-.283E+00  20.9800  -.353E+00    24.8000  -.476E+00    29.7800
   RVPZH     EMCZH       RVPZL     EMCZL       TZEMC           B
      ()     (%MC)          ()     (%MC)         (F)       (PSI)
  .80000  15.80000      .40000   7.40000    80.00000    14.43000
    IWRT         WRT       FINIS          JJ        NSBC        NCLM(I)
     ()(T OR %MC)        (%MC)          ()          ()          ()
       1   1.00000     4.00000       20000           0     1 51015   20252730
 TDBS(I)   TWBS(I)      NSD(I)     TEST(I) QRATES(I)     TZQS(I)    AIRSP(I)
     (F)       (F)          ()(T OR %MC)(G/CM2 T F)          (F)       (FT/T)
150.0000  140.0000          -1     26.9200 .2442E-02    122.4000  .2400E+05
155.0000  140.0000          -1     22.6800 .2442E-02    122.4000  .2400E+05
160.0000  140.0000          -1     19.2800 .2442E-02    122.4000  .2400E+05
165.0000  140.0000          -1     16.6000 .2442E-02    122.4000  .2400E+05
170.0000  140.0000          -1     14.0800 .2442E-02    122.4000  .2400E+05
175.0000  140.0000          -1     12.1900 .2442E-02    122.4000  .2400E+05
180.0000  140.0000          -1      5.1800 .2442E-02    122.4000  .2400E+05
    C(J)      C(J)        C(J)        C(J)        C(J)        C(J)       C(J)
   (%MC)     (%MC)       (%MC)       (%MC)       (%MC)       (%MC)      (%MC)
 32.6300    0.0000      0.0000      0.0000      0.0000      0.0000     0.0000
DZT =   .4241E-01
CBARP=   9.00
NPAS,IRFLOW,FANTIM,FANTST,IWRT,WRT,FINIS,NSBC,NCLM AND C(J) ARE IGNORED
BY KILDIF.
```

Table 3. Print-out of the initial input data to the KILSOR simulation using average moisture contents of each step in kiln Run 1.

```
       ID            DESCR(I)
        1  KILSOR  UM.DATA DOUGLAS-FIR    1984        JUNE          T=HR
      STT       WID       NPAS     IRFLOW      FANTIM      FANTST
     (IN)      (FT)        ()         ()          (T)         (T)
    .5900    2.0000         1          1     0.            .1000E+11
       SG         A         N         TW       TWDLT         TDL
       ()      (CM)        ()        (F)         (F)       (%MC)
   .44000   2.22000        24   80.00000     5.00000 500.00000
      DZT       TZD       RAE
  (CM2/T)       (F)        ()
 .4241E-01 179.38999    .65000
------FZ--------CZ  ------FZ--------CZ  ------FZ--------CZ
       ()     (%MC)        ()      (%MC)          ()       (%MC)
   1.0470    5.1800    1.0468     9.0000      1.5940     13.1400
   1.0021   17.9400    3.1650    24.8000      0.0000      0.0000
    RVPZH     EMCZH     RVPZL      EMCZL       TZEMC           B
       ()     (%MC)        ()      (%MC)         (F)       (PSI)
   .80000  16.69692    .40000    8.29692    80.00000    14.43000
     IWRT       WRT     FINIS         JJ        NSBC     NCLM(I)
      ()(T OR %MC)      (%MC)         ()          ()          ()
        1   1.00000   2.00000      20000           0    1 4 710    13142024
  TDBS(I)   TWBS(I)    NSD(I)    TEST(I) QRATES(I)       TZQS(I)    AIRSP(I)
      (F)       (F)        ()(T OR %MC)(G/CM2 T F)           (F)       (FT/T)
 150.0000  140.0000        -1    26.9200 .2442E-02      122.4000  .2400E+05
 155.0000  140.0000        -1    22.6800 .2442E-02      122.4000  .2400E+05
 160.0000  140.0000        -1    19.2800 .2442E-02      122.4000  .2400E+05
 165.0000  140.0000        -1    16.6000 .2442E-02      122.4000  .2400E+05
 170.0000  140.0000        -1    14.0800 .2442E-02      122.4000  .2400E+05
 175.0000  140.0000        -1    12.1900 .2442E-02      122.4000  .2400E+05
 180.0000  140.0000        -1     5.1800 .2442E-02      122.4000  .2400E+05
     C(J)      C(J)      C(J)       C(J)        C(J)        C(J)        C(J)
    (%MC)     (%MC)     (%MC)      (%MC)       (%MC)       (%MC)       (%MC)
  32.6300    0.0000    0.0000     0.0000      0.0000      0.0000      0.0000
CBARP= 32.63
NPAS,IRFLOW,FANTIM,FANTST,NSBC ARE IGNORED BY KILSOR.
```

to the KILDIF input except that it has been adjusted by the preceding KILDIF simulation run. The program adjusts assumed diffusion coefficient multipliers and the theoretical EMC equation [4].

The variables (Appendix D) in this paper are exactly the same as those in the user's manual for the simulations (Hart, 1983) except the variables containing "$". Because "$" can not be used in a CYBER variable, it was converted to "Z".

The sticker thickness (STT) and effective width of the stack (WID), omitting gaps, were 0.59 inch and 2 feet respectively. The other four variables listed in the third line of Table 2; NPAS (number of positions across the stack), IRFLOW (air flow direction), FANTIM (elapsed time since the last fan reversal), and FANTST (total elapsed time before each fan reversal) are ignored by KILDIF and KILSOR.

For the fourth line of the input data, the specific gravity (SG) was computed, based on oven-dry weight and water soaked volume. For this purpose, a specific gravity specimen, approximately 1.5 by 2.5 by 4 inches, was taken from each of the twelve MC samples of the first kiln charge, weighed after oven drying, and water soaked for 7 days. Afterwards, each specimen's volume was obtained by the water displacement method. Water on the surfaces of specimens was removed carefully before dipping. Their specific gravities averaged 0.44 (Appendix B). This observed value is very close to 0.45, the average specific gravity of coast type Douglas-fir published in WOOD HANDBOOK (US-FPL, 1955). The averge half-thickness (A) of the 12 boards, measured prior to drying, was 2.22 cm and 2.40 cm for the first charge and the second charge respectively. The number of cells (N) in the moisture profile was N=30 as required by KILDIF. However, for the KILSOR the input was changed to N=24 for the first charge and N=30 for the second charge. This relates to a convenient subdivision of the boards' thickness and the reasoning is explained later in the RESULTS and DISCUSSION. Initial temperature of wood (TW) was measured by the thermo-moisture meter shortly before kiln started. Maximum permissible wood temperature change per computer iteration (TWDLT) and temperature-dependent-limit (TDL) were 5°F and 500% respectively as recommended by Hart (1983). Thus, moisture movement in wood was assumed to be very temperature dependent, i.e. to occur only by diffusion.

In the fifth line of the input data, spaces for the diffusion coefficient (DZT) and the temperature at which DZT is defined (TZD) were left blank. KILDIF automatically computes these values for KILSOR and KILDRY. Relative Activation Energy (RAE) which determines the extent to which DZT changes with temperature was set at 0.65 as suggested by Hart (1983).

For the sixth lines of input data, the first CZ value should be equal to the EMC of the last drying step. This EMC was determined to be 5.18% by extrapolating the drying rate vs. the plot of average MC data of Run 1 (Fig. 4). It was used for all computer runs. The diffusion coefficient is directly proportional to the slope of the drying rate curve at a certain MC:

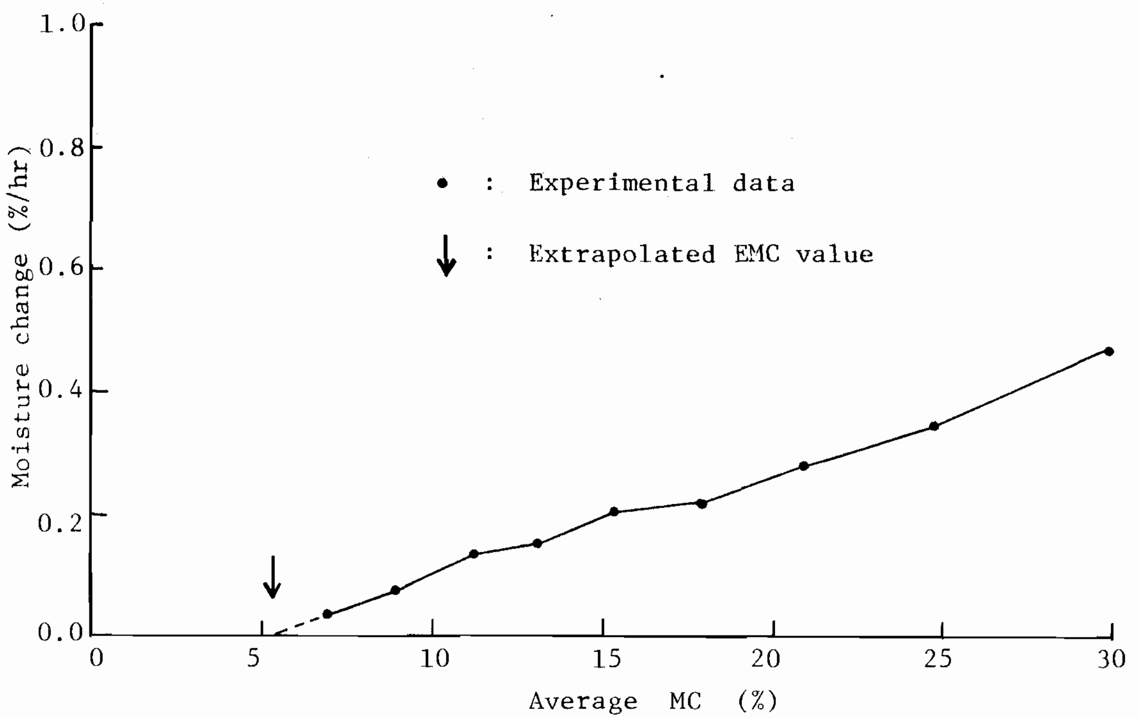

Fig. 4. EMC values determined from drying data of Run 1.

$$DZT\ (cm / hr) = (2A/\pi)^2\ b \qquad [8]$$

where A is the half thickness of the specimen (cm) and b is the slope of the drying rate curve.

Diffusion coefficient multipliers (FZ) at specially chosen MC (CZ) were roughly estimated from the drying rate versus average MC curves. However, these initially selected FZ values have very little effect on the time required to run the computer program of the KILDIF simulation and even less effect on the accuracy of the result (Hart, 1983).

When Hart developed his computer simulation, he used many small intervals within each step of the kiln schedule. In this experiment, there were no intervals within each step. Therefore, the interpolation between observed drying rates (RILRAT) at the various EMC levels were not that accurate. In this case, it was advisable to set the selected MC levels (CZ) numerically equal to the observed MC levels (CZR). An example is illustrated in Fig. 5 using the average MC of the entire stack in Run 1, and showing the EMC and nine CZR values. The two variables, RILRAT and CZR, were used for calculating accurate FZ values in the KILDIF simulation so that they did not have to be included in the KILSOR input.

The eighth line defines the simulation isotherm. Two pairs of EMC and relative vapor pressure values are sufficient to solve the isotherm equation [5]. These values were already corrected for an altitude of 500 feet elevation (Hart, 1983).

The ninth line includes the MC values which control the print out of the computed data. The print-out occurred at every 1% MC

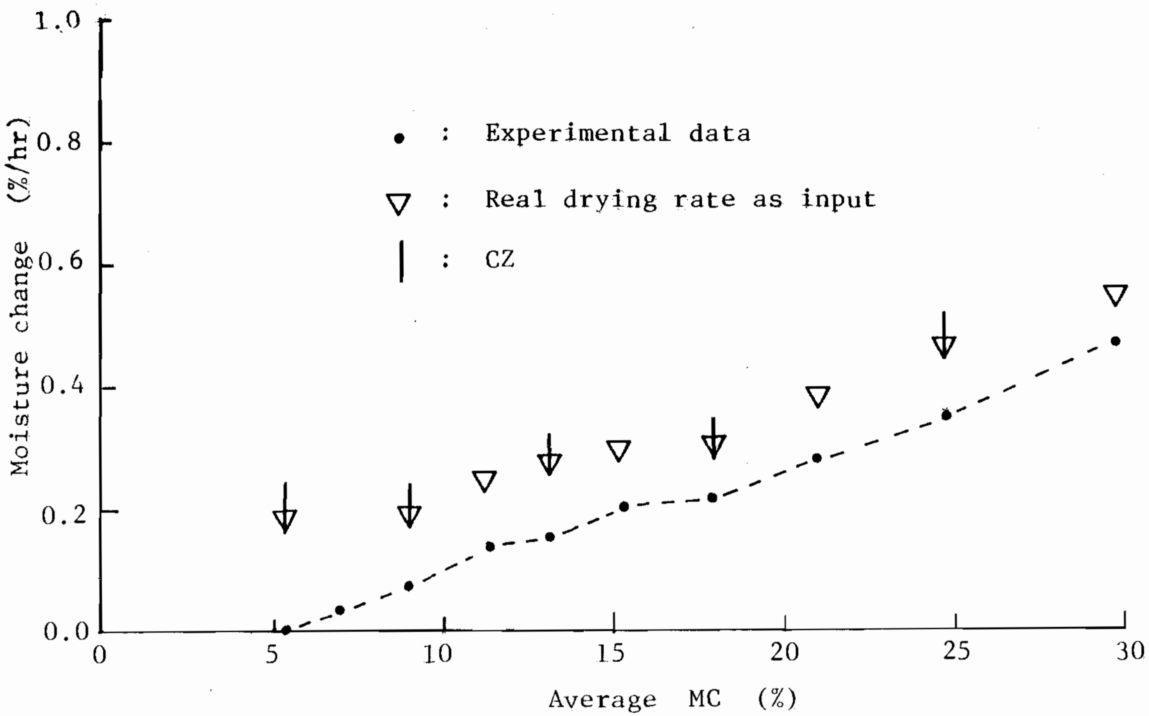

Fig. 5. MC levels (CZ) specially selected among the MC values with the observed drying rates (RILRAT). The diffusion coefficient multipliers (FZ) were determined at these CZ levels; Run 1.

(IWRT=1, WRT=1.0) until the average MC approached the value of EMC plus 2% (FINIS). The code named NSBC (number of controlling sample board) applies only to the KILDRY and not to the KILDIF and KILSOR simulations. The selected eight, out of 24 cells (NCLM),tracing the MC profile across a board in Run 1 were 1,4,7,10,13,14,20, and 24 and printed out by KILSOR. The MCs of cells 7 and 20 and the average MC of cells 13 and 14 represented the MCs in 6 mm, 18 mm, and 12 mm depth respectively. For Run 2, among the 30 cells available, the MCs of cells 8, 23 and 30, and the average MC of cells 15 and 16 were inputed for MCs in 6 mm, 18 mm, 24 mm, and 12 mm depth, respectively.

The next lines contain: environmental condition (TDBS and TWBS) of each step of the drying schedule and the MC (TEST) at which the drying condition are changed to the next step . Using equation [2], The surface transfer coefficient (QRATES) was calculated to be 0.03684 g/cm hr F. The air speed in the kiln was 400 ft/min, or 432,000 ft/hr.

The initial MCs of each cell are the variables in the last line of the simulation input. At the beginning of the simulation, uniform moisture profiles were assumed. There were two computer simulations of each kiln run. The initial MC inputs were 32.63% and 34.90% for Run 1, and 32.72% and 34.12% for Run 2.

Effect of Temperature on Moisture Content Monitored by the Thermo-moisture Meter

The effect of temperature on the readings of resistance type moisture meters has been studied by several workers (Stamm, 1927; James, 1963, 1968). Especially, the temperature correction chart (James, 1963) for readings of resistance moisture meters, based on combined data from several investigators, is very helpful. However, Forrer (1984) found that his resistance type thermo-moisture meter did not conform to this temperature correction chart. Therefore, monitored MC values by the thermo-moisture meter had to be adjusted with its own temperature correction factors to remove temperature effect. For this purpose, the temperature correction factors were determined by monitoring MC in a sample board at several kiln conditions which had the same EMC as the initial MC of the sample board.

Two sufficiently conditioned 5-inch long, 4-inch wide, and 1.5-inch thick samples were used in two seperate experiments. One was obtained from a 45-inch long Douglas-fir heartwood board dried to about 8% MC in the previous experiment and kept in a plastic bag for two weeks to remove moisture gradients in the wood. Another was obtained from a large Douglas-fir sapwood board kept for more than one year in a standard condition room; room temperature and RH were 70°F and 64% respectively.

The initial MCs of samples were 8.3% and 11.5% respectively as determined by the oven drying method. Kiln conditions at specially chosen temperatures were found in the isotherm table in the DRY KILN OPERATOR'S MANUAL (USDA Forest Service, 1961). Two stainless steel balls of 3 mm diameter were used as electrodes. Hence, according to Fig. 1, the spacing between two electrodes was 37.5 mm. The thermo-moisture meter was connected through a pair of thermocouple wires to these two electrodes which were placed 5 mm below the surface of the sample. When the monitored temperature in the sample was close to the dry bulb temperature and the monitored MC of the sample sufficiently stabilized to a certain value, the kiln condition was changed to the next drying step (Table 4). After the last drying step, the final MC value was determined by the oven drying method.

Measuring Moisture Distribution Across a Stack

This experiment was conducted in an industrial, 80 M board feet capacity kiln of Willamette Industries in Sweet Home, Oregon. The single track kiln had reversible fans and loaded four packages per truck.

As in the previous experiment in the small experimental kiln, Douglas-fir heartwood specimens were nominally 2-in by 6-in in cross section. One large 20-foot long board was taken from the green chain and cut into six 3-foot long matched samples, after cutting off 1 foot from each end. All freshly cut ends were end-coated. Four samples were used to monitor electrically the moisture gradient across the stack and two samples were weighed repeatedly for later calculation of MC changes. The samples

Table 4. Drying schedules for the two experiments on the effect of temperature on electrical moisture content readings.

1) 8.3 % MC board

Dry-bulb temp. (°F)	Wet-bulb temp. (°F)	EMC (%)
100	83	8.5
120	101	8.3
140	121	8.4
160	141	8.2
180	167	8.4

2) 11.5 % MC board

Dry-bulb temp. (°F)	Wet-bulb temp. (°F)	EMC (%)
100	89	11.2
120	109	11.5
140	129	11.4
160	150	11.5
180	171	11.6

numbered 3 and 5, MC sample boards were taken from the middle of the 20-foot board (Fig. 6), and placed in the sample pockets built two layers above the monitoring samples. The pockets were on both sides of the stack and 4 feet from the ground.

One of the purposes of this experiment was to monitor moisture gradients across the kiln load, i.e. along the path of air travel. However, to protect the thermocouple wires from damage during lumber handling, the samples were placed only in the left package (Fig. 6). Each 3-foot long sample board bore a pair of 3-mm diameter ball electrodes spaced 37.5 mm apart and inserted to a depth equal to a fourth of its thickness. These electrodes were connected through copper-constantan thermocouple wires to the thermo-moisture meter outside of the kiln. The MCs of the monitored sample boards were recorded continuously and the two MC sample boards were weighed every 12 hours.

Preparing Input Data of KILDIF and KILDRY for the Simulated Moisture Distribution Across a Stack of Lumber

Hart's simulation programs KILDIF and KILDRY were used to simulate moisture distribution across a stack. Because some input variables are used only in KILDRY, input data for KILDRY (Table 6) are somewhat different from those for KILSOR.

First of all, because the fans were reversed every 12 hours, the FANTST (total elapsed time before each fan reversal) was set 12 and airflow direction (IRFLOW) was initialized left to right.

The variables, NPAS (number of positions across the stack)

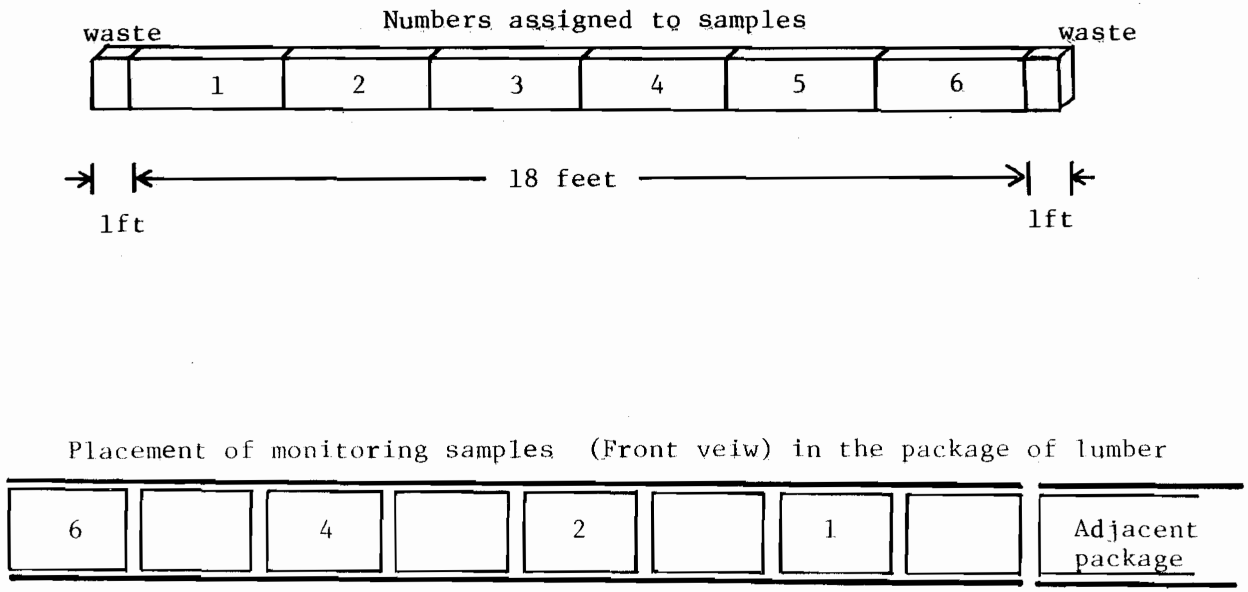

Fig. 6. Distribution of kiln samples.

Table 5. Initial KILDIF input for the experiment in the full size kiln.

```
      ID              DESCR(I)
       1  KILDIF. UM.DATA DOUGLAS-FIR    1984 OCT.   AUNADJ A      T=HR
     STT         WID        NPAS      IRFLOW     FANTIM      FANTST
    (IN)        (FT)          ()          ()        (T)         (T)
   .7500      8.0000           8           1    0.            .1200E+02
      SG           A           N          TW      TWDLT         TDL      NRUNMX
      ()        (CM)          ()         (F)        (F)       (%MC)          ()
  .44000     2.22000          30    75.00000    5.00000   500.00000           1
     DZT         TZD         RAE
 (CM2/T)         (F)          ()
 0.            0.00000      .65000
------FZ--------CZ  ------FZ--------CZ  ------FZ--------CZ
      ()       (%MC)          ()       (%MC)         ()       (%MC)
  1.0000      5.1800       .5000     15.4900     2.5000     20.1600
  2.5000     26.3600      0.0000      0.0000     0.0000      0.0000
--RILRAT-------CZR  --RILRAT-------CZR  --RILRAT-------CZR
  (%MC/T)      (%MC)     (%MC/T)       (%MC)    (%MC/T)       (%MC)
-.100E-20     5.1800   -.188E+00     15.4900  -.210E+00     17.8800
-.170E+00    20.1600   -.306E+00     23.0200  -.250E+00     26.3600
-.431E+00    30.4400   -.242E+00     34.4700  0.             0.0000
   RVPZH       EMCZH       RVPZL       EMCZL      TZEMC           B
      ()       (%MC)          ()       (%MC)        (F)       (PSI)
  .80000    15.80000      .40000     7.40000   80.00000    14.43000
    IWRT         WRT       FINIS          JJ       NSBC        NCLM(I)
      ()(T OR %MC)         (%MC)          ()         ()           ()
       1     1.00000     5.00000       20000          2     1 81115    16192330
 TDBS(I)     TWBS(I)      NSD(I)     TEST(I)  QRATES(I)     TZQS(I)    AIRSP(I)
     (F)         (F)          ()(T OR %MC)(G/CM2 T F)           (F)      (FT/T)
150.0000    140.0000          -1     33.0200  .1675E-02    122.4000   .1200E+05
155.0000    140.0000          -1     27.8500  .1675E-02    122.4000   .1200E+05
160.0000    140.0000          -1     24.8600  .1675E-02    122.4000   .1200E+05
165.0000    140.0000          -1     21.1800  .1675E-02    122.4000   .1200E+05
170.0000    140.0000          -1     19.1400  .1675E-02    122.4000   .1200E+05
175.0000    140.0000          -1     16.6200  .1675E-02    122.4000   .1200E+05
180.0000    140.0000          -1      5.1800  .1675E-02    122.4000   .1200E+05
    C(J)        C(J)        C(J)        C(J)       C(J)        C(J)        C(J)
   (%MC)       (%MC)       (%MC)       (%MC)      (%MC)       (%MC)       (%MC)
 35.9200      0.0000      0.0000      0.0000     0.0000      0.0000      0.0000
DZT =  .3642E-01
CBARP= 15.49
NPAS,IRFLOW,FANTIM,FANTST,IWRT,WRT,FINIS,NSBC,NCLM AND C(J) ARE IGNORED
BY KILDIF.
```

Table 6. Initial KILDRY input for the experiment in the full size kiln.

ID	DESCR(I)						
1	KILDRY4.UM.DATA, DOUGLAS-FIR 1984 OCT UNADJ 2 A T=HR						0
STT	WID	NPAS	IRFLOW	FANTIM	FANTST		
(IN)	(FT)	()	()	(T)	(T)		
.7500	8.0000	8	1	0.	.1200E+02		
SG	A	N	TW	TWDLT	TDL		
()	(CM)	()	(F)	(F)	(%MC)		
.44000	2.22000	9	75.00000	5.00000	500.00000		
DZT	TZD	RAE					
(CM2/T)	(F)	()					
.3642E-01	174.22548	.65000					
------FZ	--------CZ	------FZ	--------CZ	------FZ	--------CZ		
()	(%MC)	()	(%MC)	()	(%MC)		
.9386	5.1800	.9361	15.4900	.0826	20.1800		
2.7520	26.3600	0.0000	0.0000	0.0000	0.0000		
RVPZH	EMCZH	RVPZL	EMCZL	TZEMC	B		
()	(%MC)	()	(%MC)	(F)	(PSI)		
.80000	16.69692	.40000	8.29692	80.00000	14.43000		
IWRT	WRT	FINIS	JJ	NSBC	NCLM(I)		
()	(T OR %MC)	(%MC)	()	()	()		
1	1.00000	7.00000	20000	2	1 2 3 4	5 6 8 9	
TDBS(I)	TWBS(I)	NSD(I)	TEST(I)	QRATES(I)	TZQS(I)	AIRSP(I)	
(F)	(F)	()	(T OR %MC)	(G/CM2 T F)	(F)	(FT/T)	
150.0000	140.0000	-1	33.0200	.1675E-02	122.4000	.1200E+05	
155.0000	140.0000	-1	27.8500	.1675E-02	122.4000	.1200E+05	
160.0000	140.0000	-1	24.8600	.1675E-02	122.4000	.1200E+05	
165.0000	140.0000	-1	21.1800	.1675E-02	122.4000	.1200E+05	
170.0000	140.0000	-1	19.1400	.1675E-02	122.4000	.1200E+05	
175.0000	140.0000	-1	16.6200	.1675E-02	122.4000	.1200E+05	
180.0000	140.0000	-1	5.1800	.1675E-02	122.4000	.1200E+05	
C(J)	C(J)	C(J)	C(J)	C(J)	C(J)	C(J)	
(%MC)	(%MC)	(%MC)	(%MC)	(%MC)	(%MC)	(%MC)	
35.9200	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	

CBARP= 35.92

and NSBC (number of sample board controlling the simulation), are used by KILDRY only. A layer consisted of 16 boards, 8 in each adjacent package. Their MCs were simulated at eight positions. The simulated program of drying was controlled by two boards located at the edges of the package, that is where the air enters and where it leaves the stack. This corresponds to Code 2 of Hart's simulation program, one of four possible codes in variable NSBC.

The most important input variables for KILDIF are RILRAT and CZR to determine FZ values at the selected CZ MC levels. Table 7 shows the drying rates derived from MC averages of the two MC samples, and the initial diffusion coefficient multipliers (FZ) estimated from the plot of drying rate versus MC at four selected MC levels (CZ) (Fig.7).

When the drying rates simulated by KILDRY did not agree with the observed drying rates, the RILRAT values were adjusted by the equations [10] and [11] (see the next section) and KILDIF and KILDRY were rerun. To compare the drying rates observed and simulated by KILDRY, each simulated drying rate (RATE-SBK) must be determined over a 12 hour period, as was the observed drying rate. It was done by changing the print-out interval to 12 hours.

Table 7. Drying rates derived from MC averages of two samples and diffusion coefficient multipliers (FZ) at selected MC levels(CZ).

CZ (%)	Average MC (%)	Drying rate (%MC/hr)	FZ
	34.47	- 0.242	
	30.44	- 0.431	
26.26	26.36	- 0.250	2.5
	23.02	- 0.306	
20.16	20.16	- 0.170	2.5
	17.88	- 0.210	
15.49	15.49	- 0.188	0.5
5.18	5.18	0.	1.0

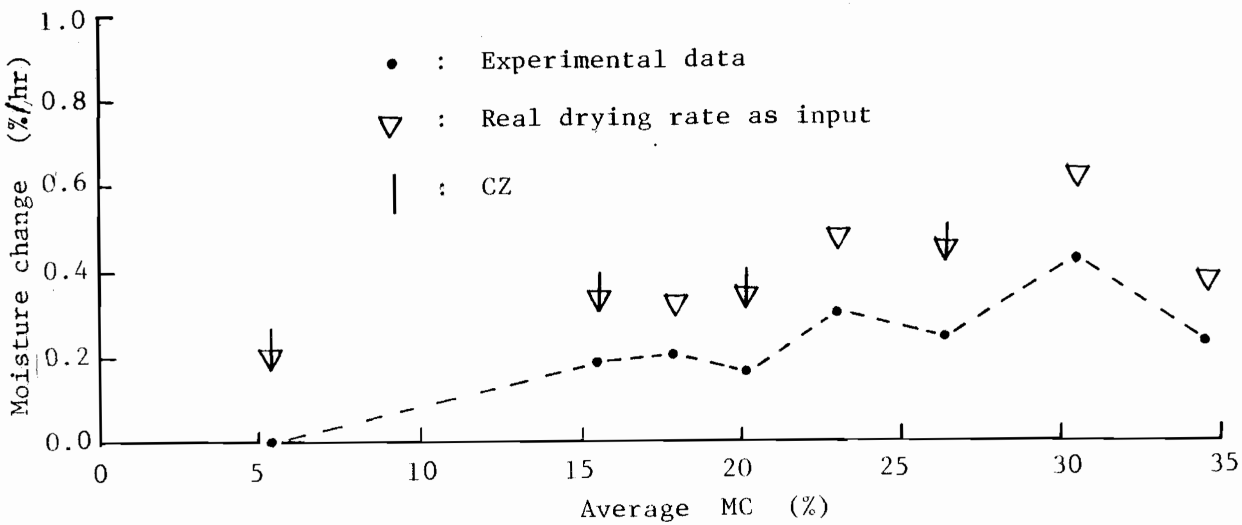

Fig. 7. MC levels (CZ) specially selected among the MC values with the observed drying rates (RILRAT). The diffusion coefficient multipliers (FZ) were determined at these CZ levels; Industrial kiln run.

RESULT AND DISCUSSION

Stress Patterns

The main purpose of the stress pattern test was to know when the drying stress reversal occurred. The accurate knowledge of drying stress behavior would help to develop drying schedules. As mentioned before, after the reversal of drying stresses, the humidity can be decreased without danger of surface checking, a major drying defect of Douglas-fir (Espenas, 1952).

The stress patterns of twelve sample boards are shown at 12 hour intervals (Fig. 8). The graphs indicate if the shell is in compression, tension or stress free. As expected, the sample boards did not all show the same drying stress behavior. During the first three steps of drying, the shell of all 12 samples was stressed in tension. Between 36 hrs and 48 hrs, eight boards showed stress reversal from tension to compression. Between 48 hrs and 60 hrs, three additional boards reversed stresses and the last board had finally followed after 60 hrs. In terms of MC, the stress reversal of board 2 occurred at the highest MC of 18.2 % (Fig. 8). However, most boards had stress reversals between 15 % - 17 % MC. Because the average MC at 60 hrs is 14.55 % the drying condition could be accelerated after this time.

After leaving prong sections exposed for 24-hour at ambient conditions of the laboratory, all prongs indicated severe case-hardening except those cut from boards dried for 12 hrs only. Therefore, a conditioning treatment is needed after the final

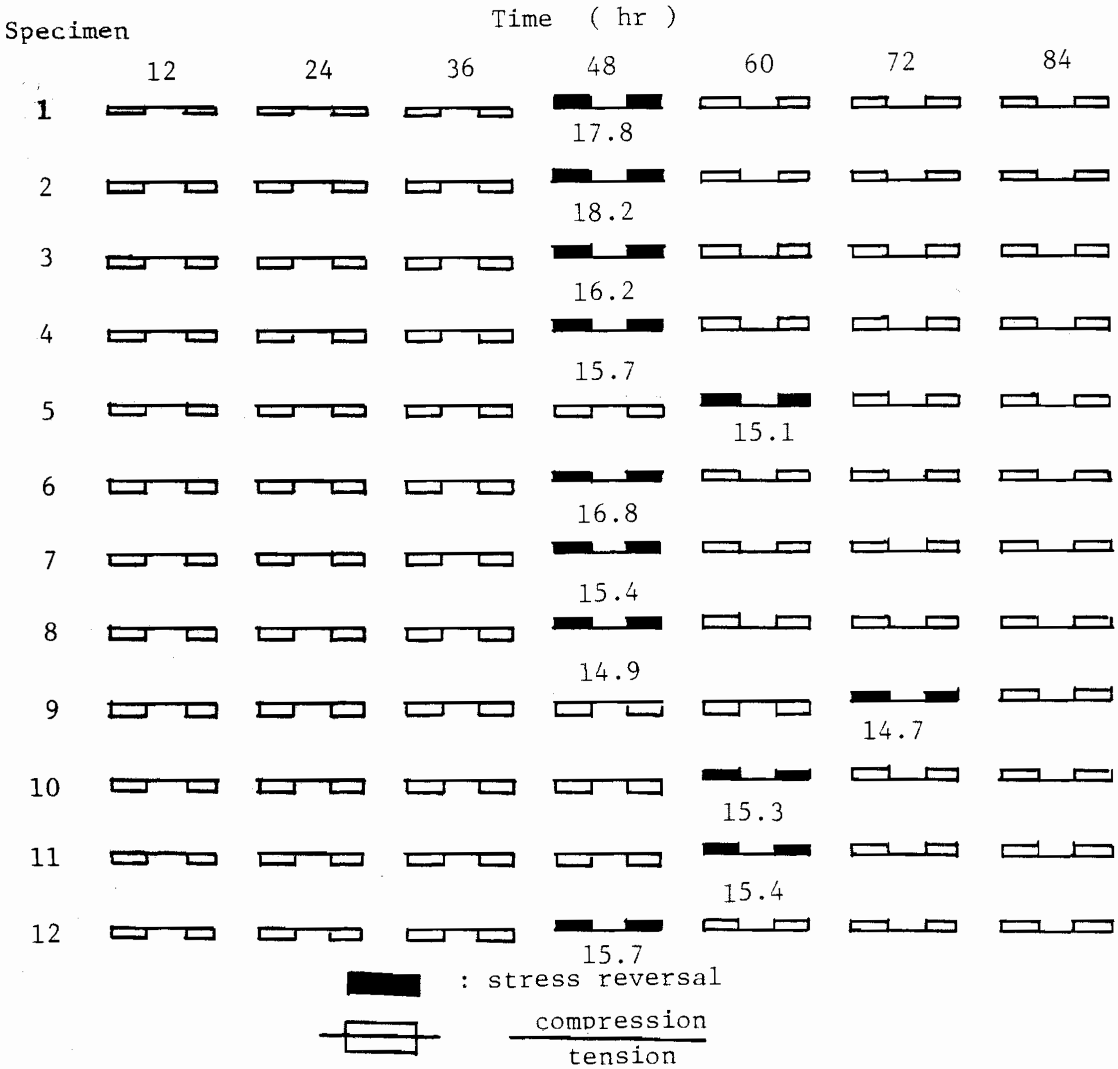

Fig. 8. Stress patterns in twelve sample boards at every 12 hours and MC values when stress reversals were found.

drying step, if stress relief is desired.

Temperature Correction for Moisture Content Monitored by the Thermo-moisture Meter

MC readings monitored by the thermo-moisture meter were strongly influenced by temperature (Figs.9 and 10): MC readings increased with a decrease in the electric resistance of wood due to higher wood temperature.

After the heating experiment, the samples' MCs were determined to be 8.3% and 10.8% by the oven drying method. In other words, the sample with 8.3% initial MC did not change its MC, but the sample with an initial MC of 11.5 lost 0.7% moisture during the process (Fig. 9 and Fig 10). Fig. 10 shows that the sample lost 0.7% moisture only at the second step (Dry bulb 120 F, Wet bulb 109 F) and no MC change occurred at any other step. Therefore, the MC readings of the 11.5% MC sample need to be adjusted after second step by adding 0.7% MC. The adjusted data are shown in Table 8.

A statistical analysis for paired samples showed that there was no significant difference in temperature correction for MC readings between the two MC levels.

Corrections for MC readings were plotted against wood temperature in Fig. 11, and the regression model with the best fit was chosen from the family regression program on the HP-9825 microcomputer. The regression equation and the coefficient of correlation are below:

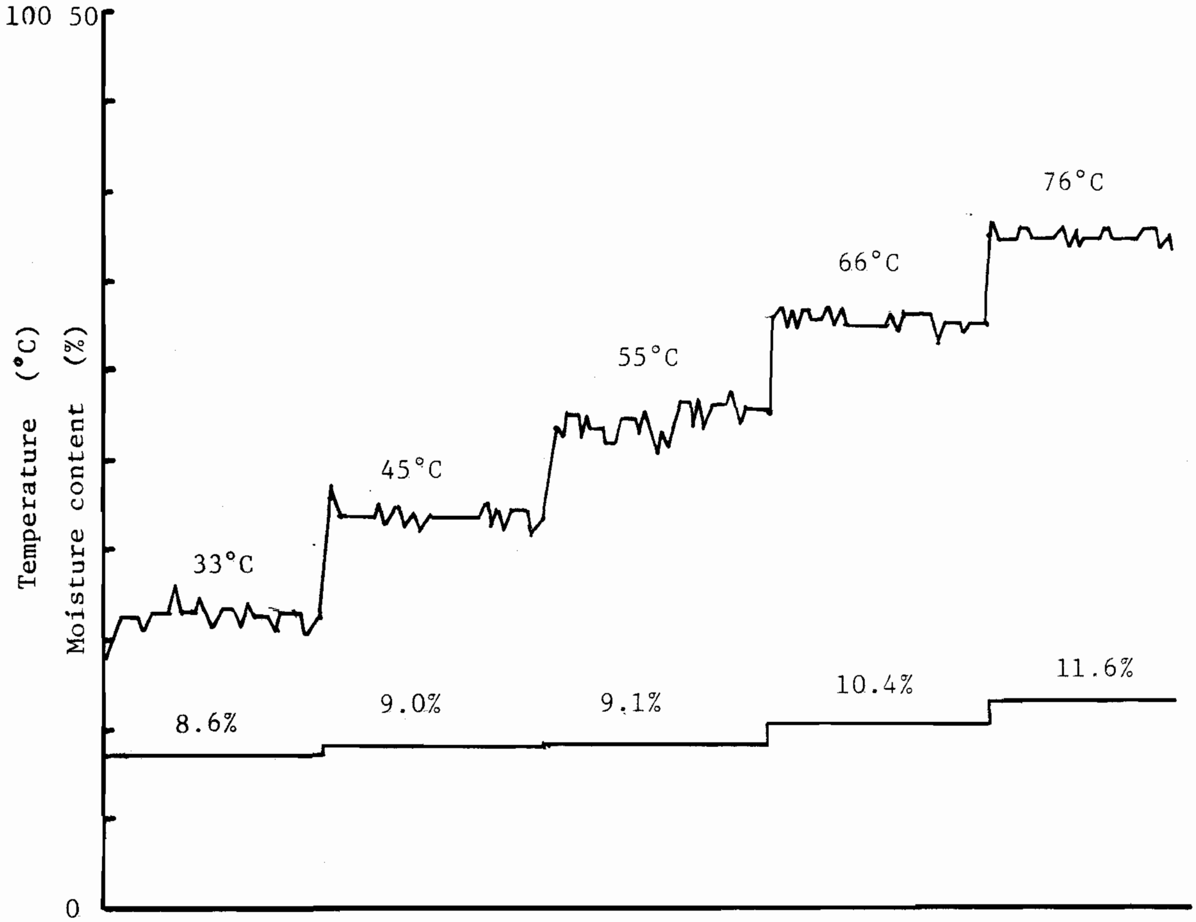

Fig. 9. Moisture content values monitored by the thermo-moisture meter at several wood temperature levels when the kiln conditions were maintained at 8.3% EMC.

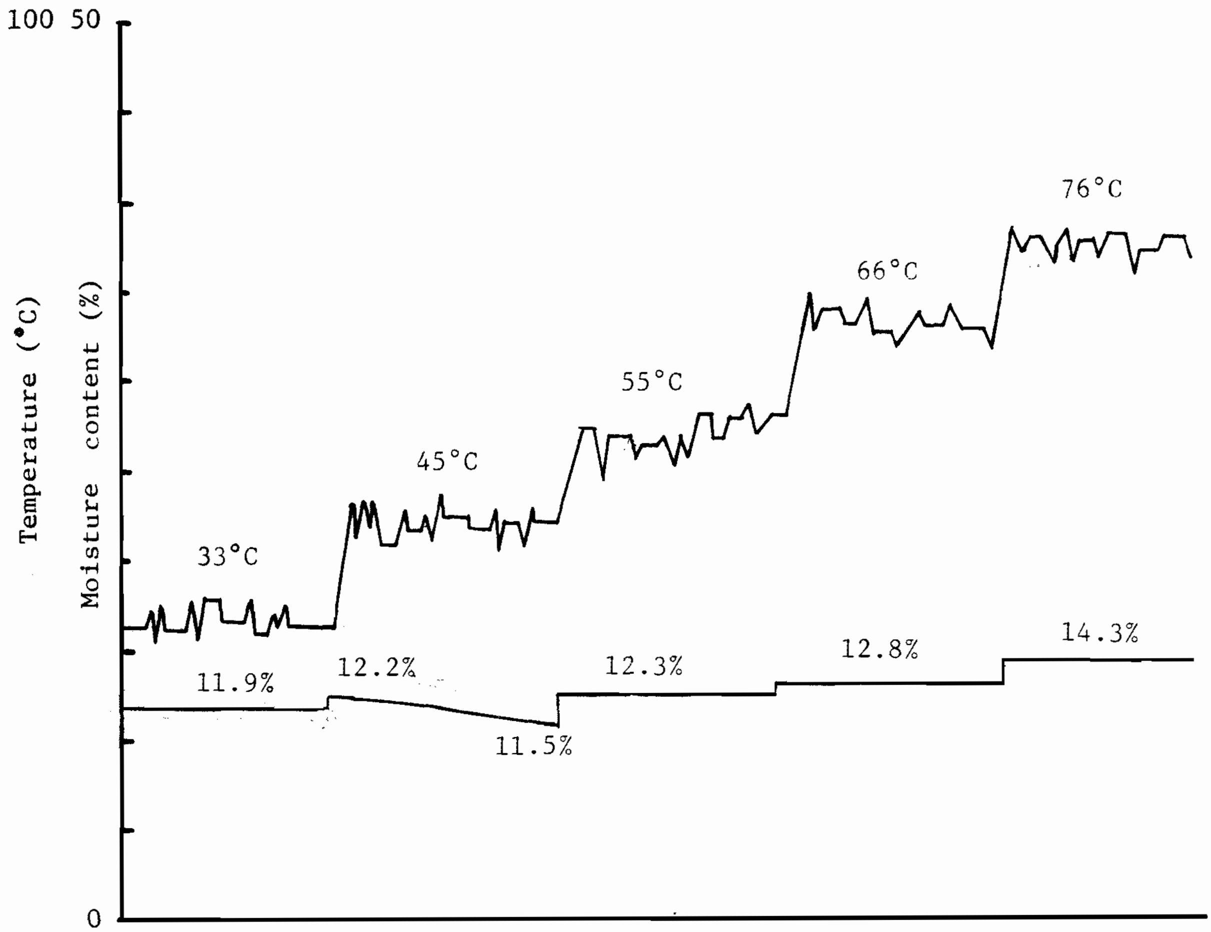

Fig. 10. Moisture content values monitored by the thermo-moisture meter at several wood temperature levels when the kiln conditions were maintained at 11.5% EMC.

Table 8. Temperature corrections for readings with the thermo-moisture meter at two MC and six wood temperature levels.

Wood temperature (°F)	MC level 8.3 %	11.5 %
	MC correction (%)	
70	0	0
92	0.3	0.4
113	0.7	0.7
131	0.8	1.5
151	2.1	2.0
168	3.3	3.5

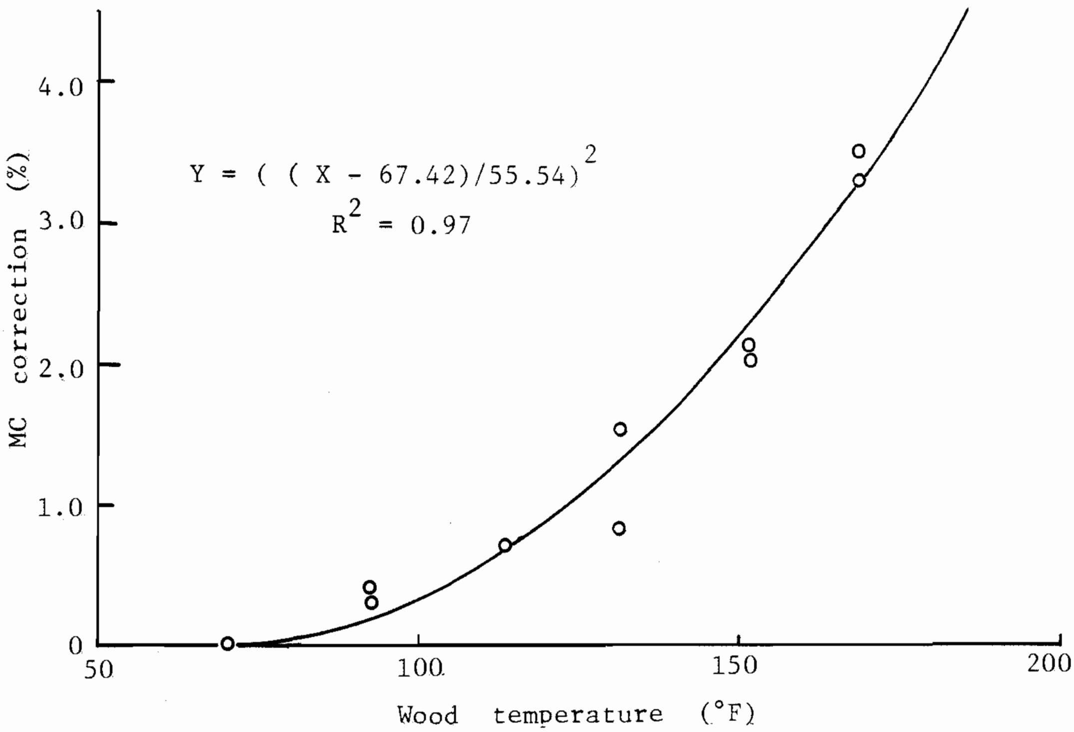

Fig. 11. Correction for MC readings with the thermo-moisture meter at various temperatures.

$$Y = \left(\left(X - 67.42 \right) / 55.54 \right)^2 \quad ....[9]$$

$$R^2 = 0.97$$

where X = temperature of wood (°F)
Y = temperature correction factor (% MC) .

Moisture Gradients in a Board

1) Monitored by the Thermo-Moisture meter

The moisture distribution in the monitored boards during drying Runs 1 and 2 are presented in Figs. 12 and 13 respectively. All monitored moisture values are corrected for the effect of temperature using equation [9].

The moisture content values electrically monitored at the 24 mm electrode level were not plotted for Run 1 (Fig.12). As shown in Fig.14, due to the placement of the 24 mm depth electrode beyond the center of the board, the MCs monitored at that level did not reflect the MCs at the center of the monitored board and were very close to those monitored at 18mm depth.

Fig. 12 also shows that the moisture content near the surface decreased quickly after a short warm-up period of about 1.5 hours, whereas the moisture content measured by the two middle electrodes decreased smoothly. The maximum moisture gradient between the center and the surface electrodes occurred after about 17 hours, while the moisture gradient between the two middle electrodes did not change much until 61 hours.

The drying curve for the entire board in Run 1 is almost parallel to the drying curves determined with the middle electrodes. It shows that the compensated moisture values are of good agreement with the moisture values obtained by weighing the sample boards in the entire moisture range of the Run 1.

In Run 2, the initial warm-up period lasted 3.5 hours during

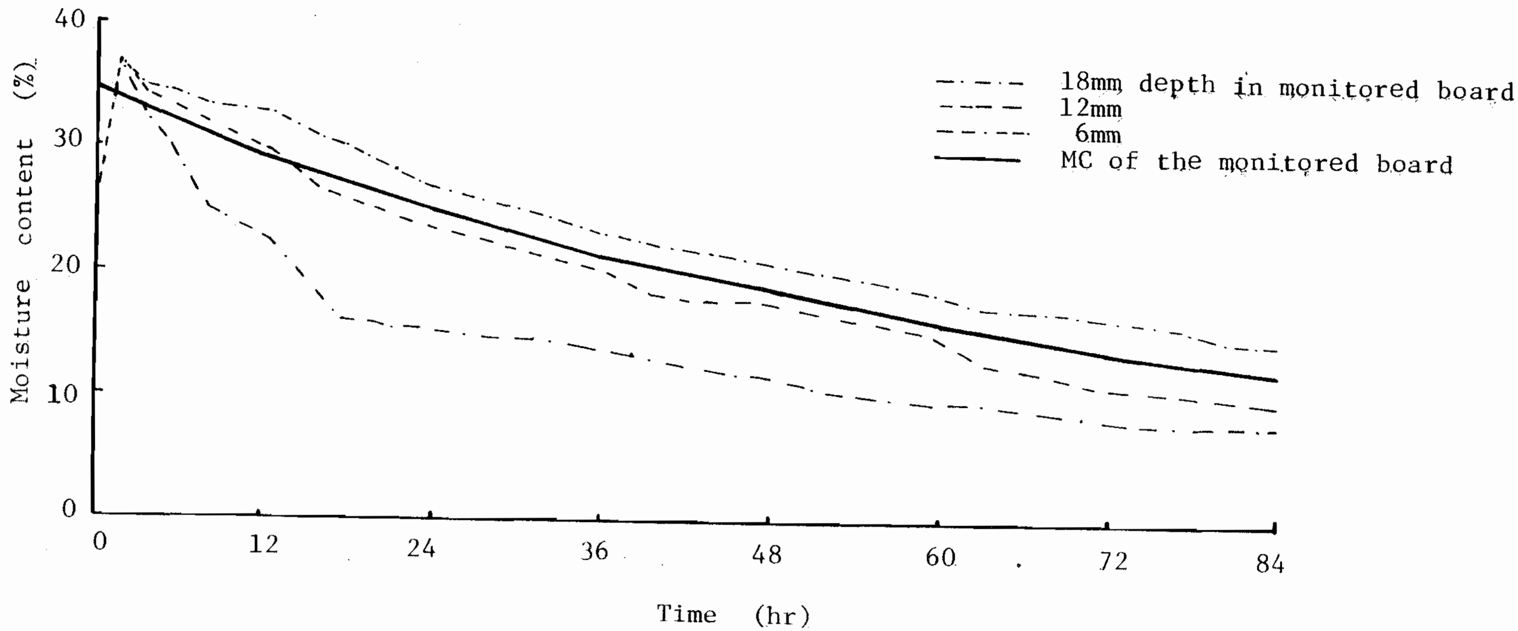

Fig. 12. Moisture distribution in the sample board monitored by the thermo-moisture meter, and its drying curve obtained through periodic weighing; Run 1.

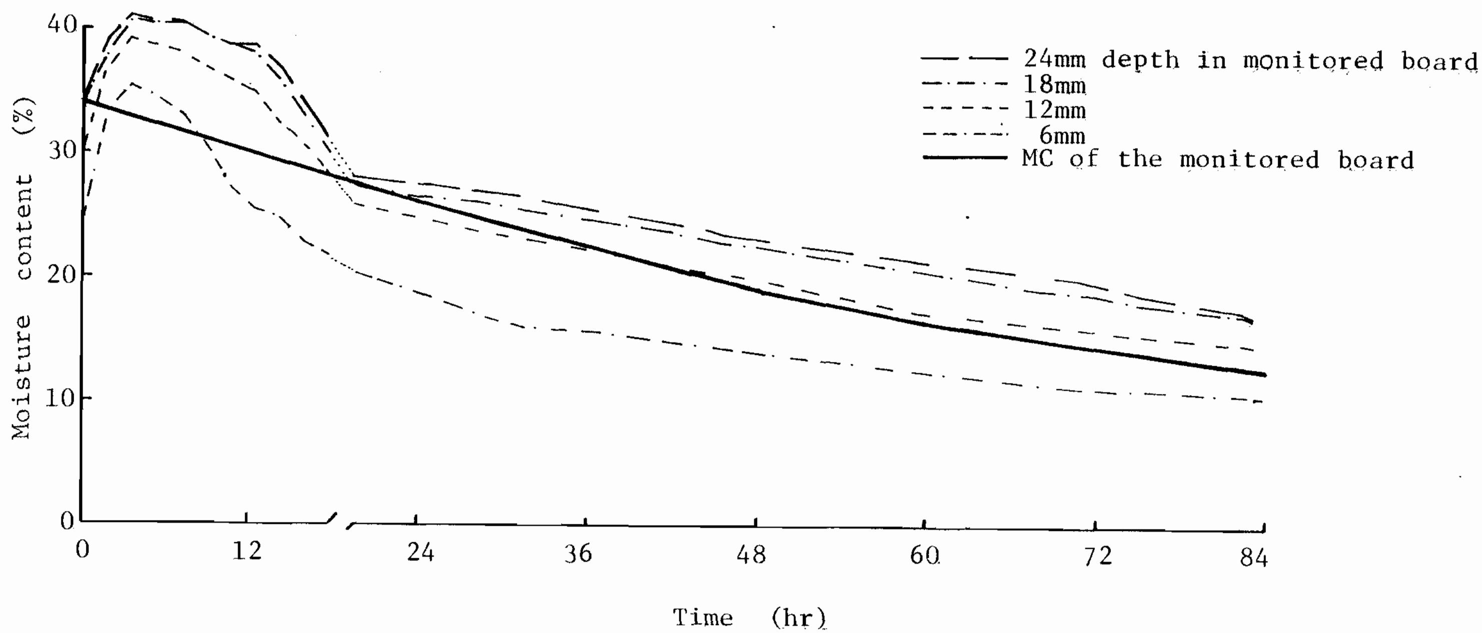

Fig. 13. Moisture distribution in the sample board monitored by the thermo-moisture meter, and its drying curve obtained through periodic weighing; Run 2.

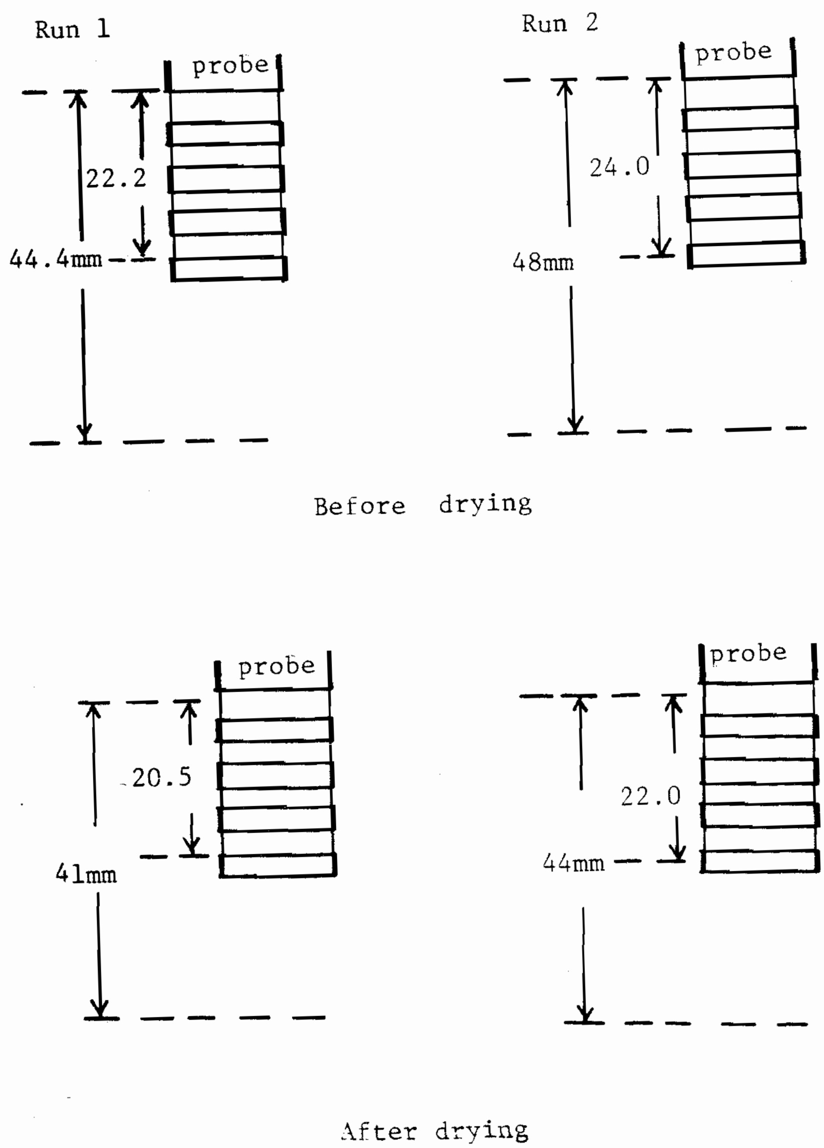

Fig. 14. Thickness dimensional changes of sample boards and the locations of electrodes before and after drying.

which the moisture gradients increased. Because the kiln run was interrupted after 15 hours of drying, the moisture gradients were lower than expected after the second drying step.

2) Prediction by the Simulation

The ultimate goal of a simulation program is that its results have suitable application to the real world. For this purpose the simulated drying rates in KILSOR were compared to the real observed drying rates (initial RILRAT). If they differed too much from each other, the RILRAT data must be adjusted in the direction of the desired change and the KILDIF and KILSOR simulation rerun.

The real drying rates should be observed after they have settled down following changes in kiln conditions (Hart, 1983). Differences between the real and simulated rates were also anticipated here because there was only one value, without further refinement, for each step of the kiln schedule. To improve the fit of the simulated rates to the RILRAT values, the adjusted RILRAT's, R1, for a second computer iteration of KILDIF were calculated from the formula

$$R1 = R0 * (R0 / S0) \quad \ldots\ldots\ldots\ldots\ldots\ldots [10]$$

where, R0 = initial RILRAT value
S0 = simulation rate of first KILSOR run
R1 = adjusted RILRAT for second KILDIF run

When a second adjustment of drying rates was needed, the following equation was used

R2 = R1 * (RO / S1) ....[11]

where, R2 = second adjusted RILRAT value for the third KILDIF simulation

Tables 9 through 12 show the successive adjustments of the drying rates simulated by KILSOR to the observed drying rates. The last simulated drying rates were fairly close to RO. Figs. 15 through 22 present the adjusted drying rates versus average MCs and the MCs versus time of kiln runs 1 and 2. The second iteration of both computer simulations agreed fairly well with observed data. However, discrepancies still existed between simulated and actual drying curves at the very beginning of drying. They may be explained by possible water condensation on wood surfaces, at that time such condensation is considered in the simulation program, but did not last long enough to be measured at the first weighing after 12 hours. These well adjusted KILSOR moisture distributions were plotted in Figs 23 through 26. In the computer simulation, the maximum moisture gradients between the surface and the center of the monitored boards occurred at about 12 hours, and then the gradients decreased gradually, however, increasing again slightly toward the end of both kiln runs (Figs. 24 and 26). In contrast, the simulated drying curves using the average MCs of twelve boards as input declined smoothly (Figs. 23 and 25).

These differences between the simulations may be due to the fact that: the single monitored sample boards had higher initial MCs and lower drying rates than the averages of all boards.

Table 9. Successive adjustments of drying rates to simulate observed drying rates of 12 boards; Run 1 in the experimental kiln.

CZR (%)	R0 (%/hr)	S0 (%/hr)	R1 (%/hr)	S1 (%/hr)
29.78	-0.476	-0.8626	-0.263	-0.6466
24.80	-0.353	-0.4071	-0.306	-0.3535
20.98	-0.283	-0.3408	-0.235	-0.2756
17.94	-0.223	-0.2771	-0.179	-0.2216
15.94	-0.210	-0.2230	-0.198	-0.1822
13.14	-0.158	-0.1918	-0.130	-0.1605
11.35	-0.141	-0.1737	-0.144	-0.1436
9.00	-0.0811	-0.0955	-0.0689	-0.0800

Table 10. Successive adjustments of drying rates to simulate observed drying rates of the monitored board; Run 1 in the experimental kiln.

CZR (%)	R0 (%/hr)	S0 (%/hr)	R1 (%/hr)	S1 (%/hr)
32.28	-0.451	-0.7446	-0.273	-0.7559
27.35	-0.357	-0.3737	-0.341	-0.3669
23.43	-0.297	-0.2915	-0.303	-0.2420
20.30	-0.225	-0.2612	-0.194	-0.2507
17.60	-0.226	-0.2246	-0.227	-0.2002
15.25	-0.166	-0.2039	-0.135	-0.1688
13.32	-0.155	-0.1910	-0.126	-0.1471
10.54	-0.100	-0.1116	-0.0896	-0.0896
8.05	-0.0512	-0.0614	-0.0427	-0.0544

Table 11. Successive adjustments of drying rates to simulate observed drying rates of 12 boards; Run 2 in the experimental kiln.

CZR (%)	R0 (%/hr)	S0 (%/hr)	R1 (%/hr)	S1 (%/hr)	R2 (%/hr)	S2 (%/hr)
30.22	-0.416	-0.7771	-0.223	-0.7603	-0.122	-0.502
25.28	-0.408	-0.4409	-0.3780	-0.3980	-0.387	-0.352
21.21	-0.273	-0.3314	-0.225	-0.2887	-0.213	-0.250
18.24	-0.223	-0.2672	-0.186	-0.2301	-0.180	-0.197
15.73	-0.196	-0.2248	-0.171	-0.1909	-0.176	-0.155
13.58	-0.162	-0.1958	-0.134	-0.1660	-0.131	-0.141
11.88	-0.122	-0.1789	-0.0832	-0.1526	-0.0665	-0.139
9.80	-0.100	-0.1112	-0.0900	-0.0967	-0.093	-0.116

Table 12. Successive adjustments of drying rates to simulate observed drying rates of the monitored board; Run 2 in the experimental kiln.

CZR (%)	R0 (%/hr)	S0 (%/hr)	R1 (%/hr)	S1 (%/hr)
32.08	-0.341	-0.7493	-0.155	-0.4053
28.12	-0.319	-0.4116	-0.247	-0.3364
24.42	-0.298	-0.3272	-0.271	-0.2797
20.97	-0.278	-0.2853	-0.271	-0.2536
18.03	-0.213	-0.2545	-0.178	-0.2334
15.73	-0.170	-0.2232	-0.130	-0.2028
13.88	-0.138	-0.2001	-0.0952	-0.1444
11.39	-0.123	-0.1279	-0.118	-0.09472
8.39	-0.0583		-0.0561	-0.09472

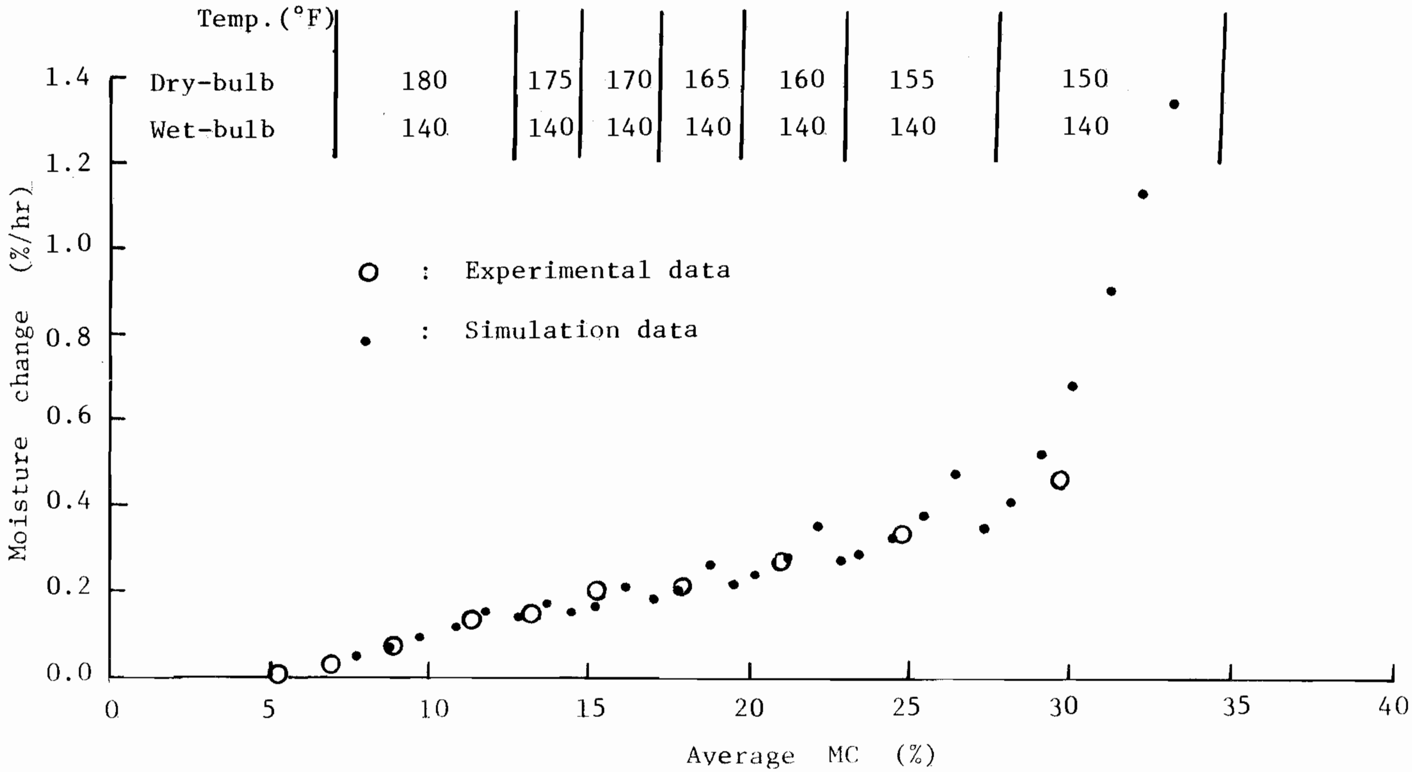

Fig. 15. Drying rate versus average MC : Last adjusted computer simulation data and actual average of 12 boards dried in the experimental kiln; Run 1.

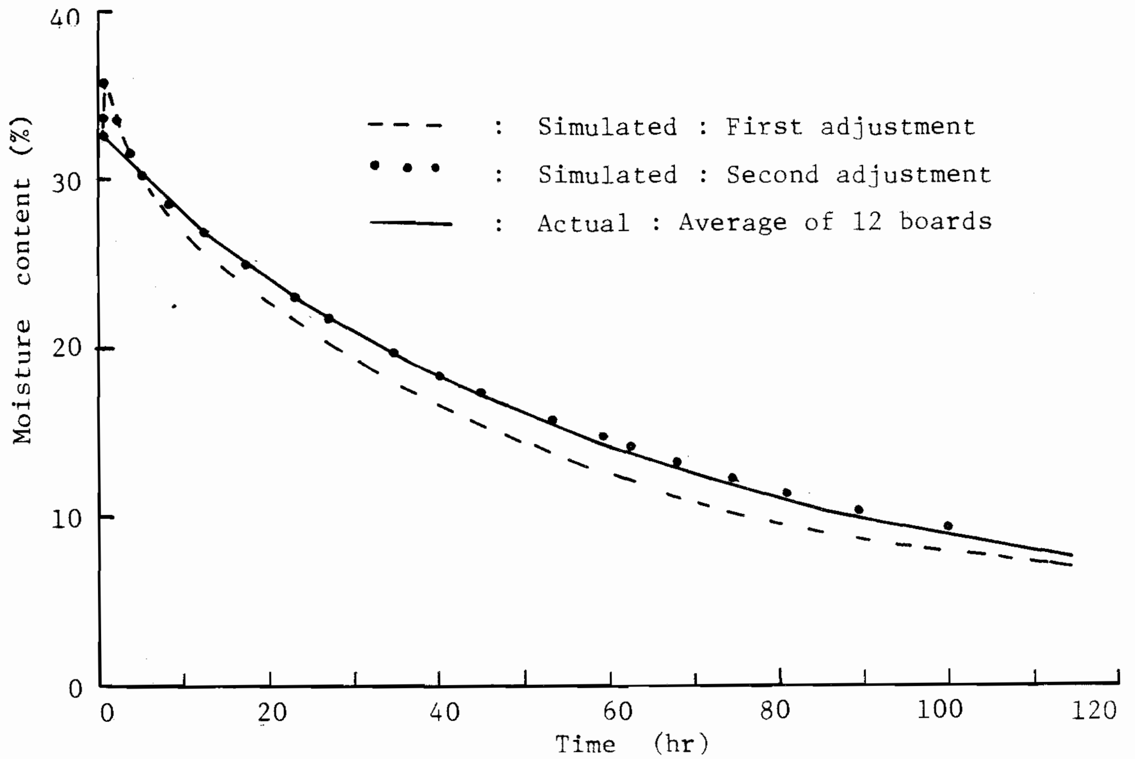

Fig. 16. Simulated and actual drying curves; Run 1.

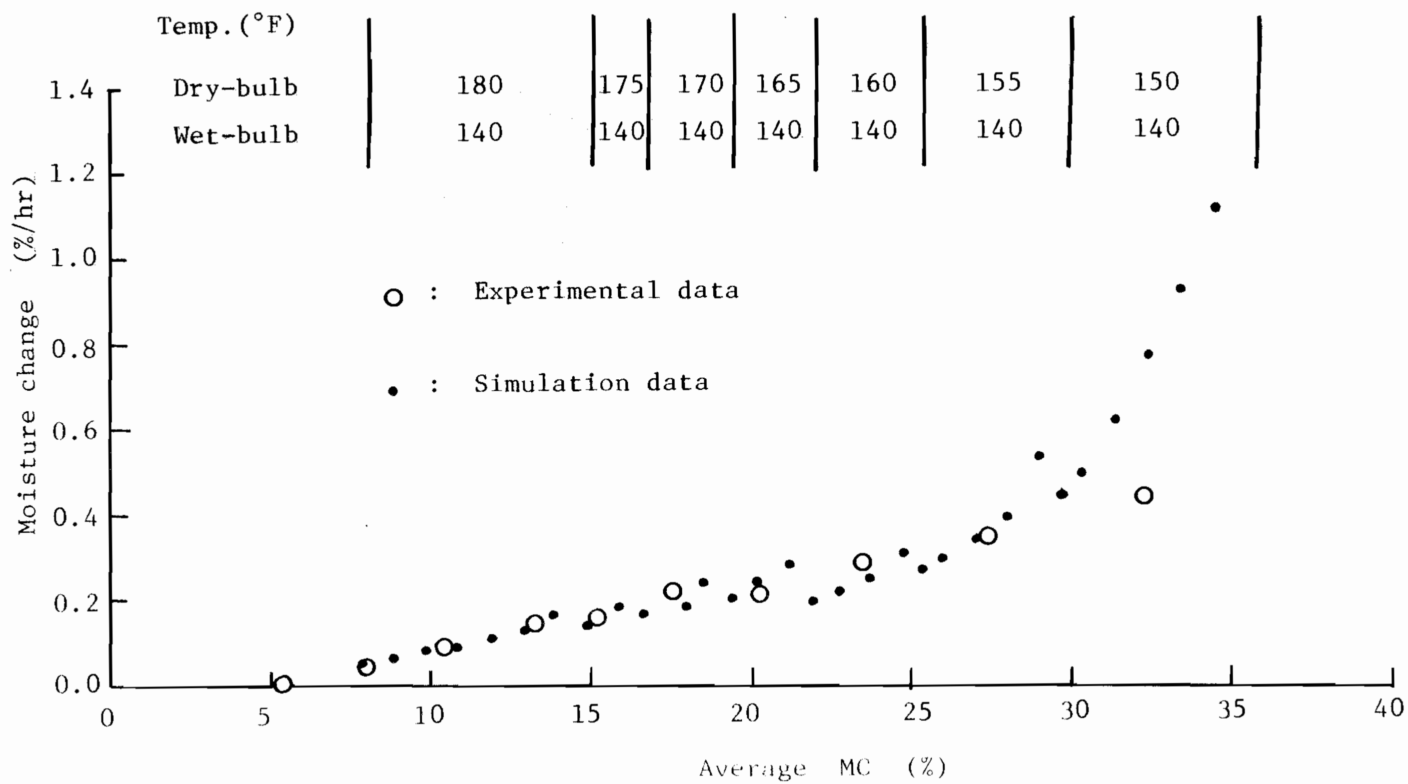

Fig. 17. Drying rate versus average MC : Last adjusted computer simulation data and actual of the monitored sample board dried in the experimental kiln; Run 1.

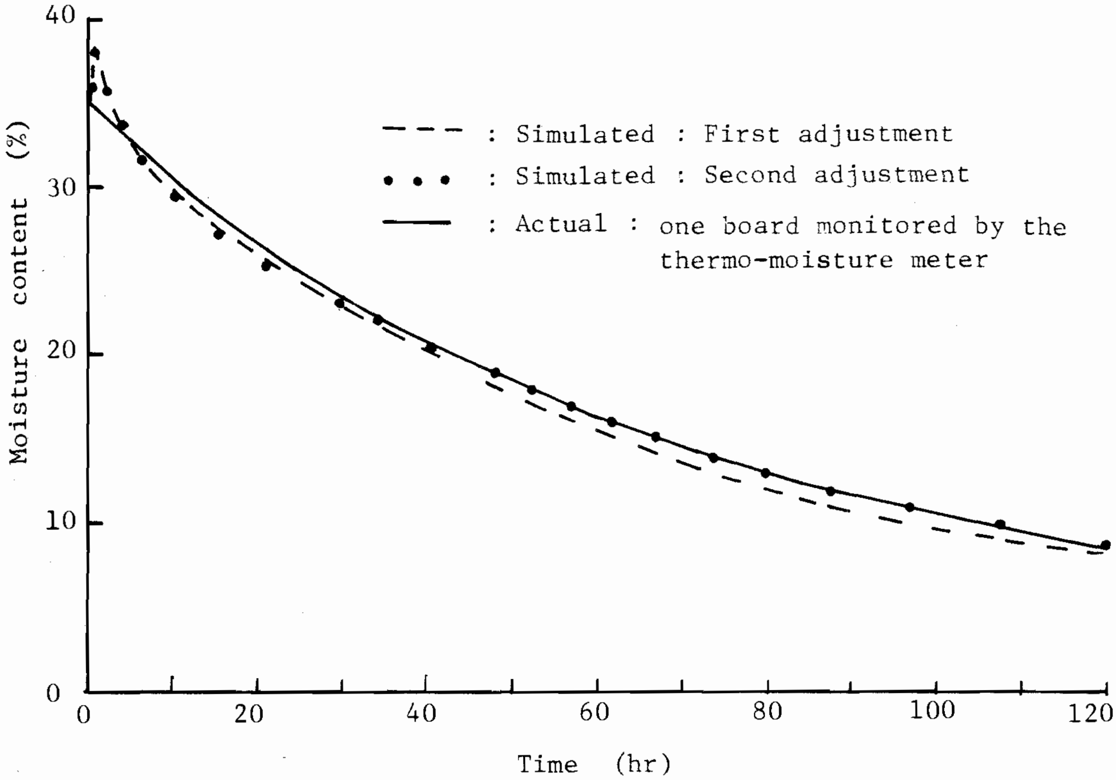

Fig. 18. Simulated and actual drying curves of the monitored sample board; Run 1.

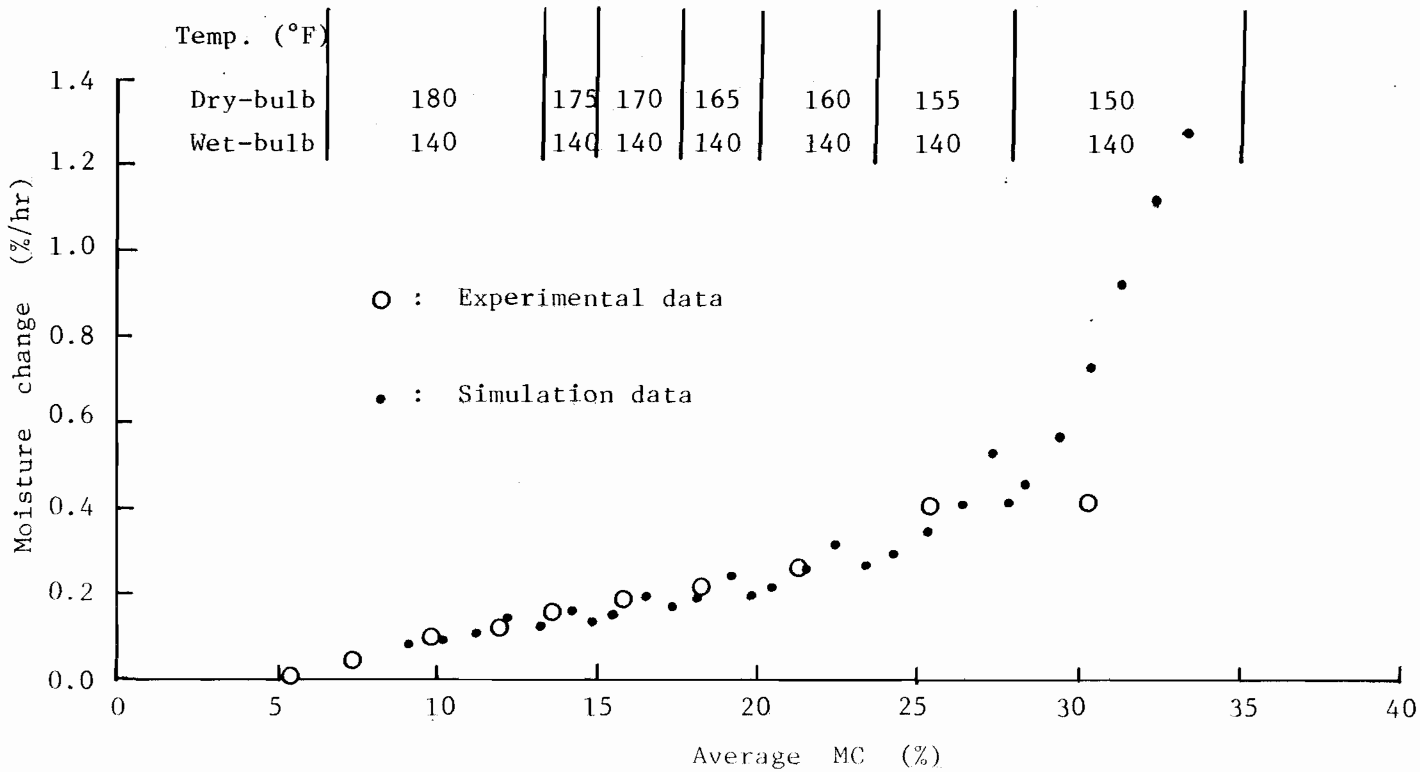

Fig. 19. Drying rate versus average MC : Last adjusted computer simulation data and actual average of 12 boards dried in the experimental kiln; Run 2.

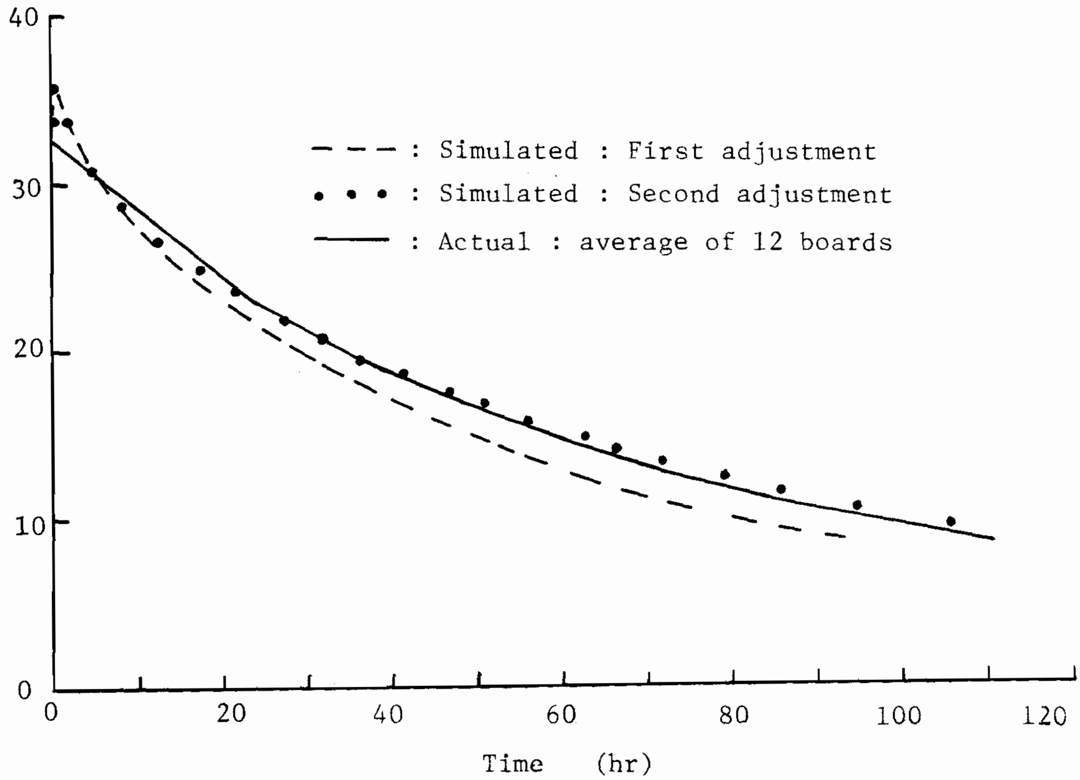

Fig. 20. Simulated and actual drying curves; Run 2.

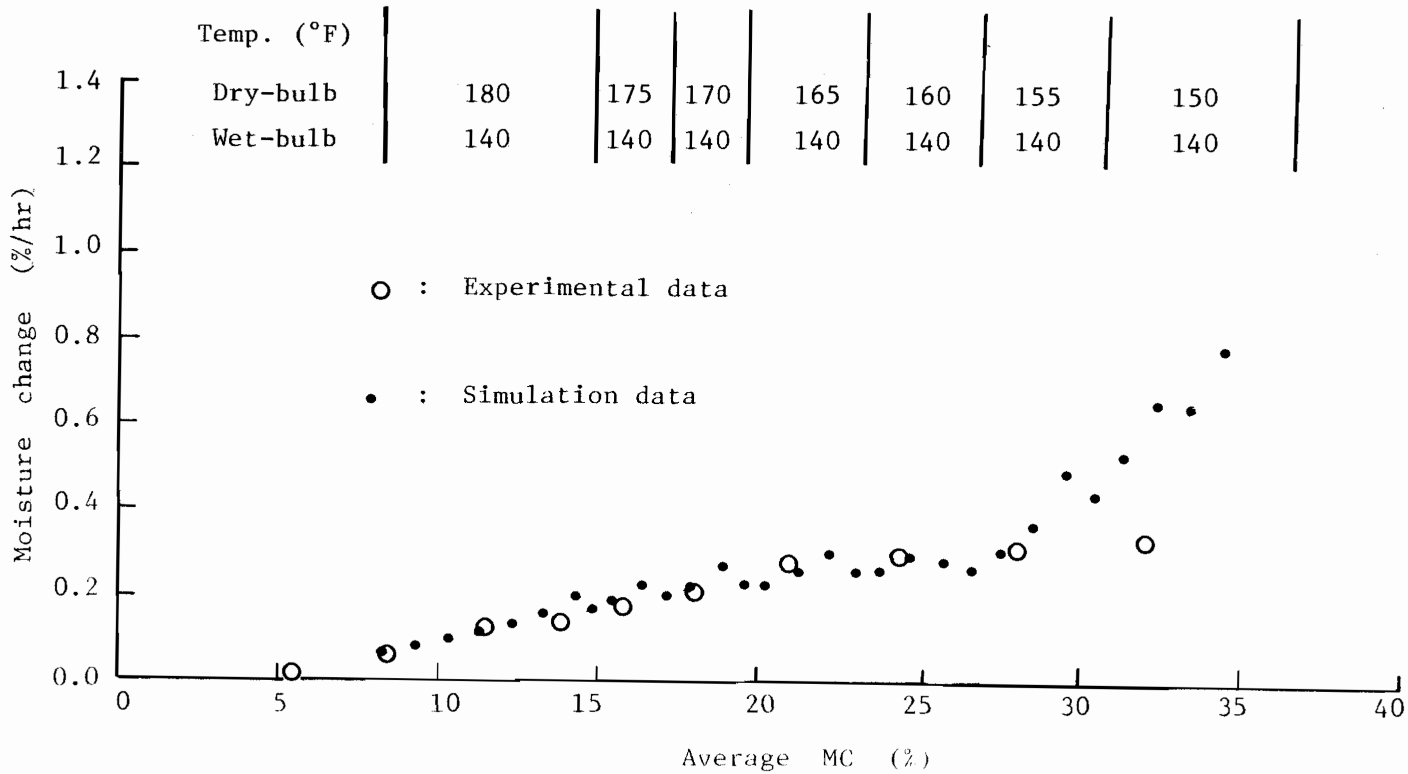

Fig. 21. Drying rate versus average MC: Last adjusted computer simulation data and actual data of the monitored sample board dried in the experimental kiln; Run 2.

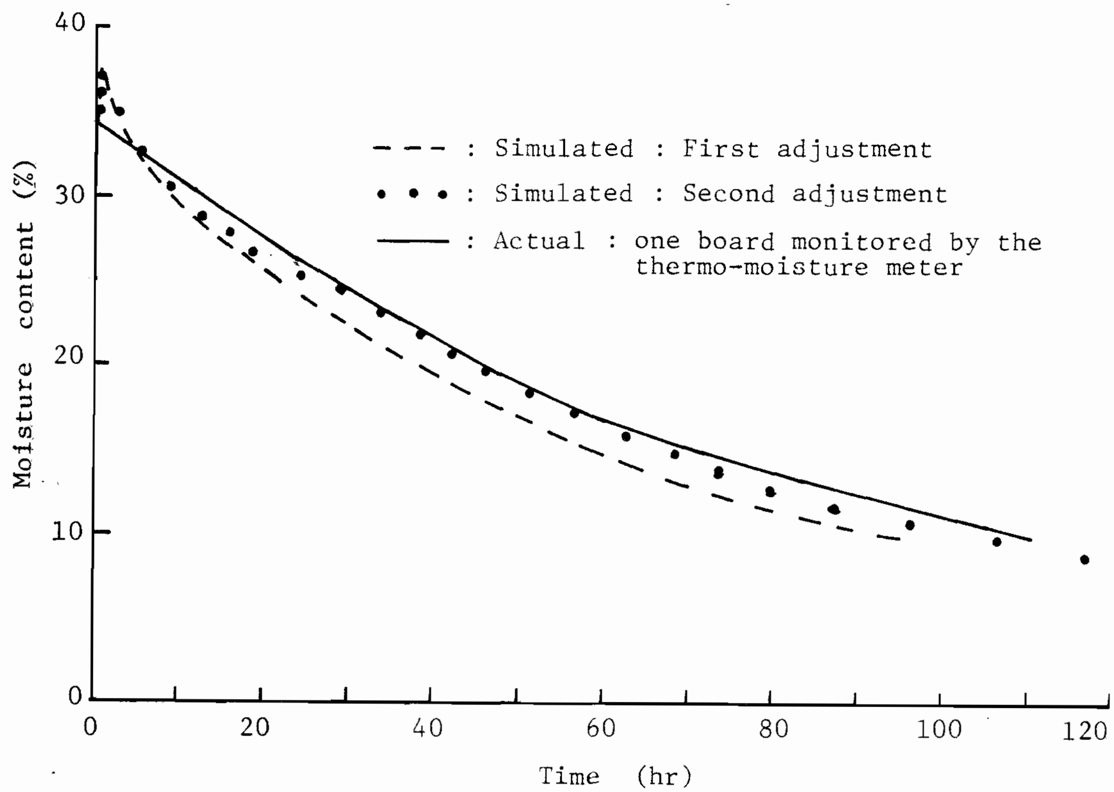

Fig. 22. Simulated and actual drying curves of the monitored sample board; Run 2.

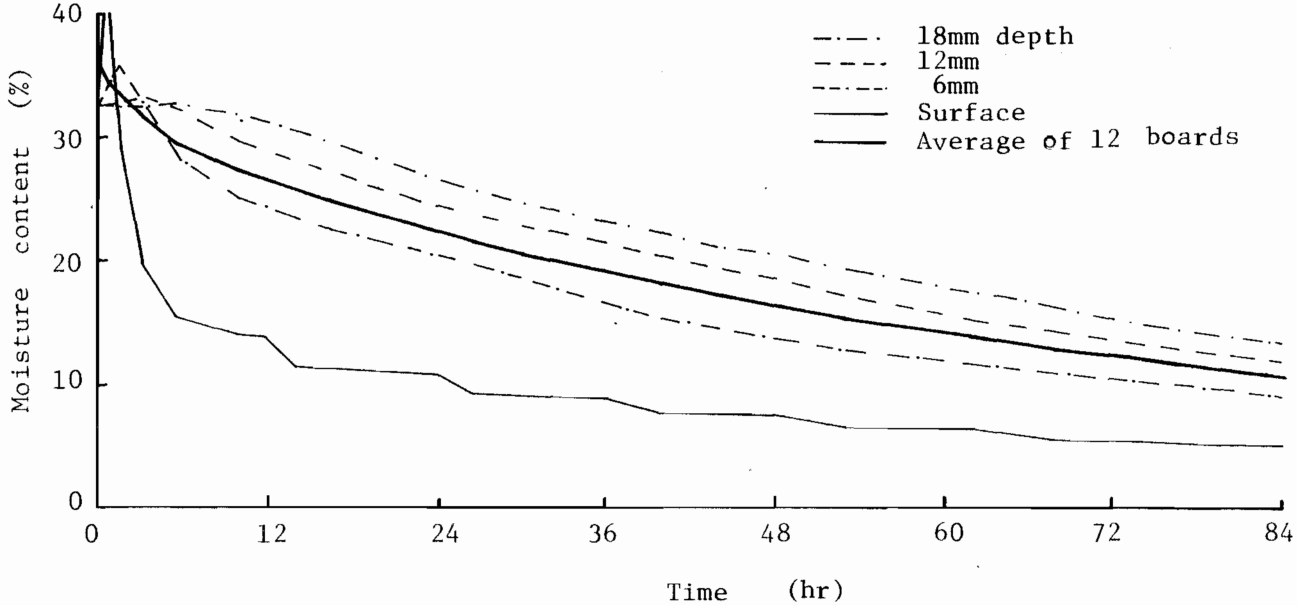

Fig. 23. Moisture distribution in a board simulated from the MC average of 12 boards in Run 1

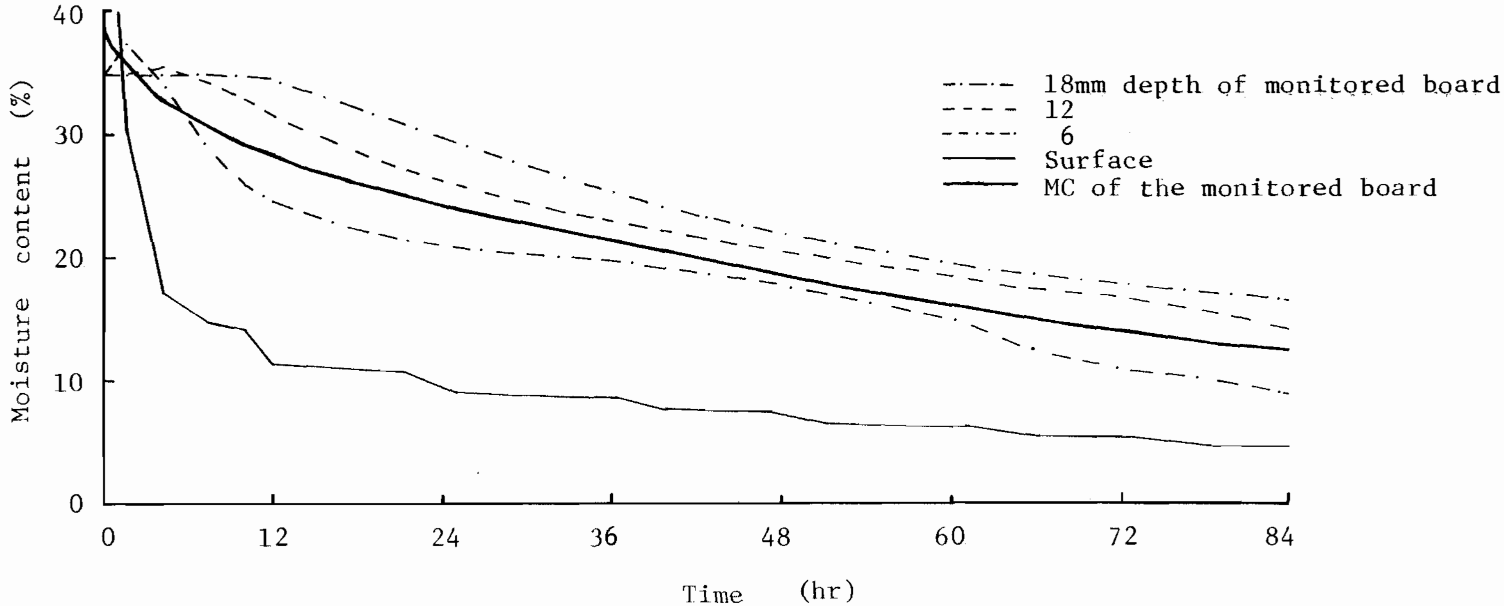

Fig. 24. Moisture distribution in a board simulated from the MC of the monitored sample in Run 1.

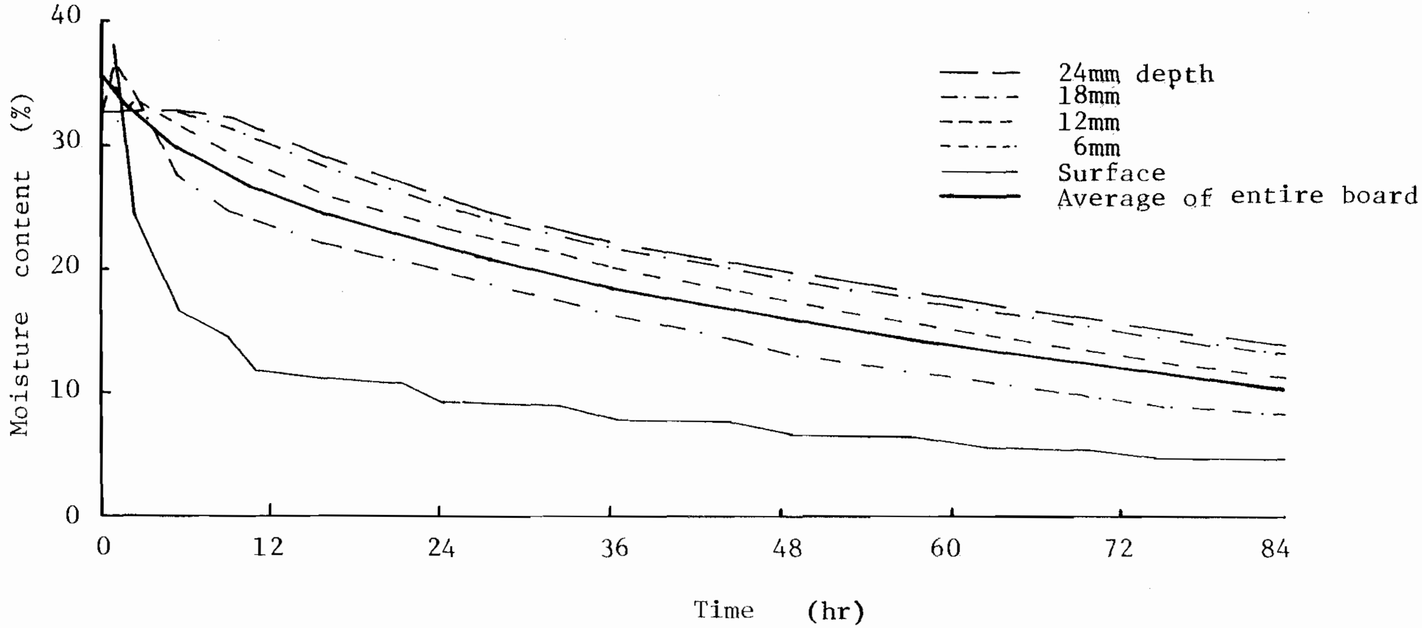

Fig. 25. Moisture distribution in a board simulated from the MC average of 12 boards in Run 2.

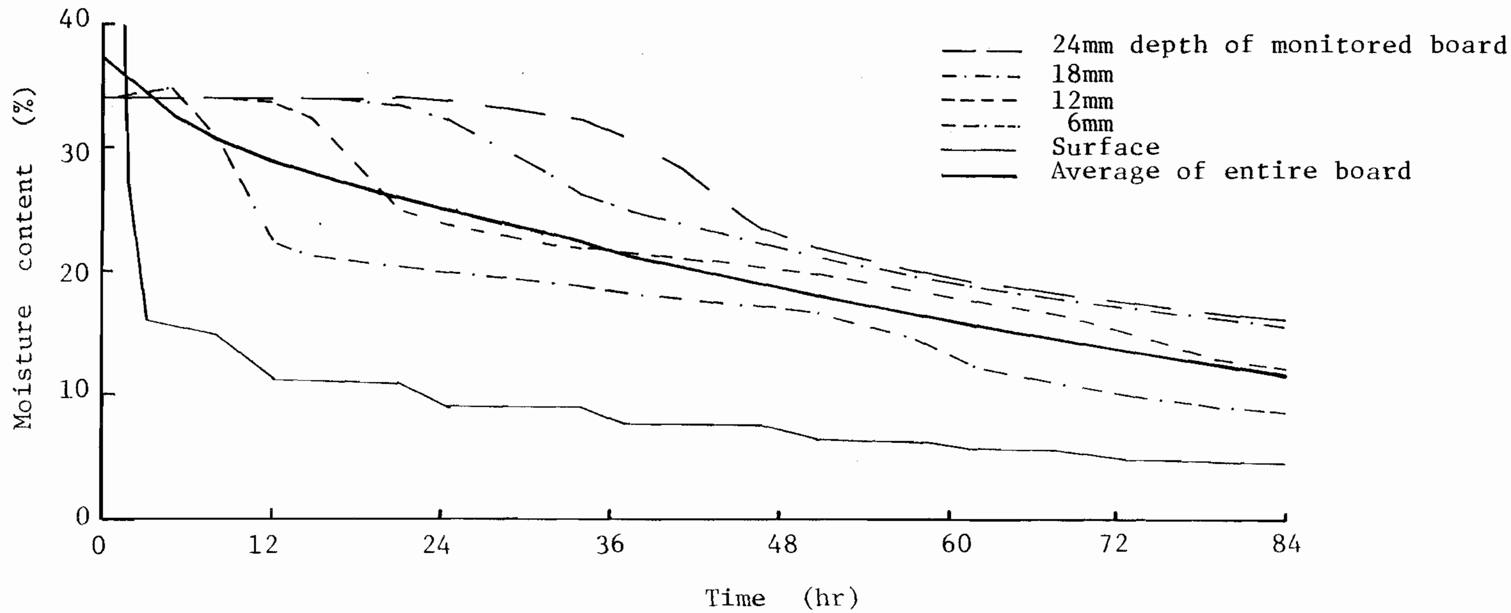

Fig. 26. Moisture distribution in a board simulated from the MC of the monitored sample in Run 2.

3) Comparing Observed and Simulated Results

One difficulty occurs when comparing the monitored and simulated moisture gradients at certain MCs. Wood changes its dimension during drying below the FSP. As shown in Fig. 14, the monitoring sample boards shrink around 8 % of their original thicknesses and the surface electrodes were found only 4.3 mm or 4.0 mm below the surfaces after drying.

Instead of quantitative comparison of the MC values predicted by the simulation and monitored by the thermo-moisture meter, the moisture gradient behavior might be examined. The monitored and simulated MCs and gradients are summarized in Tables 13 and 14. The moisture gradients as monitored by the thermo-moisture meter generally decreased as the average MC decreased. However, as mentioned before, the simulated moisture gradients did not simply decrease as the actual average MC decreased: They reached a minimum at 48 hours and then they increased slightly.

The computer simulations also predict wood temperature assumed to be uniform across the board thickness, at each print-out interval. The predicted wood temperature is computed by subtracting the energy consumed for sorption from the dry-bulb temperature in the kiln. However, the temperatures monitored electrically at a depth of 6 mm below the surface were 5 to 7°F lower than the predicted values (Table 15). This may have been caused by temperature nonuniformity in the kiln. There is no doubt that a temperature gradient exists from the air intake to the exit

Table 13. Moisture values monitored every 12 hours by the thermo-moisture meter for Runs 1 and 2 in the experimental kiln.

Run 1.

Drying Time (hr)	Electrode depth (mm)				
	6		12		18
	MC values and differences (%)				
12	22.8		30.0		33.1
		7.2*		10.3	
24	16.0		24.1.		27.5
		8.1		11.5	
36	14.4		20.8		23.9
		6.4		9.5	
48	12.3		18.3		21.6
		6.0		9.3	
60	10.1		16.2		19.2
		6.1		9.1	
72	9.3		11.8		17.4
		2.5		8.1	
84	8.8		10.4		15.2
		1.6		6.4	

Run 2.

Drying Time (hr)	Electrode depth (mm)						
	6		12		18		24
	MC values and differences (%)						
12	25.7		35.1		38.3		38.8
		9.4		1.6		13.1	
24**	19.1		25.1		27.0		17.8
		6.0		7.9		8.7	
36	16.0		22.6		25.0		25.9
		6.6		9.0		9.9	
48	14.6		20.3		23.2		23.8
		5.7		8.6		9.2	
60	12.9		17.8		21.0		22.1
		4.9		8.1		9.2	
72	11.8		16.6		19.4		20.4
		4.8		7.6		8.6	
84	11.0		15.3		17.6		17.7
		4.3		6.6		6.7	

* : Values between columns are moisture differences from the the moisture values in 6mm depth.
** : Kiln was shut down between 12 and 24 hrs.

Table 14. Moisture values predicted every 12 hours by the computer simulation for Run 1 and Run 2 in the experimental kiln.

Run 1.

Drying Time (hr)	Electrode depth (mm)				
	6		12		18
	MC values and differences (%)				
12	26.1		32.9		23.7
		6.8*		8.6	
24	21.6		27.2		20.8
		5.6		9.2	
36	19.8		23.1		25.4
		3.3		5.6	
48	18.0		20.7		22.2
		2.7		4.2	
60	15.0		18.4		19.5
		3.4		4.5	
72	11.1		16.7		17.9
		5.6		6.8	
84	9.3		13.5		17.9
		4.2		7.0	

Run 2.

Drying Time (hr)	Electrode depth (mm)						
	6		12		18		24
	MC values and differences (%)						
12	23.9		34.2		34.1		34.1
		10.3		10.2		10.2	
24	20.6		25.2		33.7		34.1
		4.6		13.1		13.5	
36	19.0		22.3		26.4		32.6
		3.3		7.4		13.6	
48	17.6		20.7		22.7		23.8
		3.1		5.1		6.2	
60	14.9		18.7		19.9		20.2
		3.8		5.0		5.3	
72	11.2		16.8		18.1		18.5
		5.6		6.9		7.3	
84	9.4		13.4		16.5		17.0
		4.0		7.1		7.6	

* : Values between columns are moisture differences from the moisture values in 6 mm depth.

Table 15. Comparison of computer predicted and actually monitored wood temperatures at 6 mm below the board surface during Run 1.

Drying time (hr)	DB (°F)	Wood temperature (°F)		
		Predicted	Monitored	Difference
12	150	147	140	7
24	155	153	147	6
36	160	159	153	6
48	165	164	158	6
60	170	169	163	6
72	175	174	169	5
84	180	179	172	7

side of a lumber stack even in a small kiln, mainly because the air cools while absorbing moisture.

One of the problems encountered with the computer simulation was the difficulty in finding drying rates (RILRAT) as input. As mentioned before, RILRAT values must be determined after the sample boards settle down to the new drying conditions of every drying step. However, since the drying rate used as input is only an average value for a 12 hour period of a particular drying step, it may not be very accurate. Of course, the smaller the interval, the more accurate will be the drying rate input. Also at the beginning of drying, the warm-up period was included in the period over which the drying rate was averaged. Nevertheless, this is not too critical because one can rerun the simulaton program a number of times with more closely adjusted drying rates until they approach the observed drying rates.

Moisture Distribution Across a Stack of Lumber

1) Monitored by the Thermo-Moisture Meter

Fig. 27 shows the moisture distribution among the four monitored boards in one horizontal layer in the stack. The MC curves are already corrected for temperature measured by the kiln's recorder-controller because the temperature monitoring function in the thermo-moisture meter unfortunately malfunctioned. The six matched boards were expected to have the same initial MCs, but they ranged from 32.5 % to 41.2 % (Appendix C). However, this

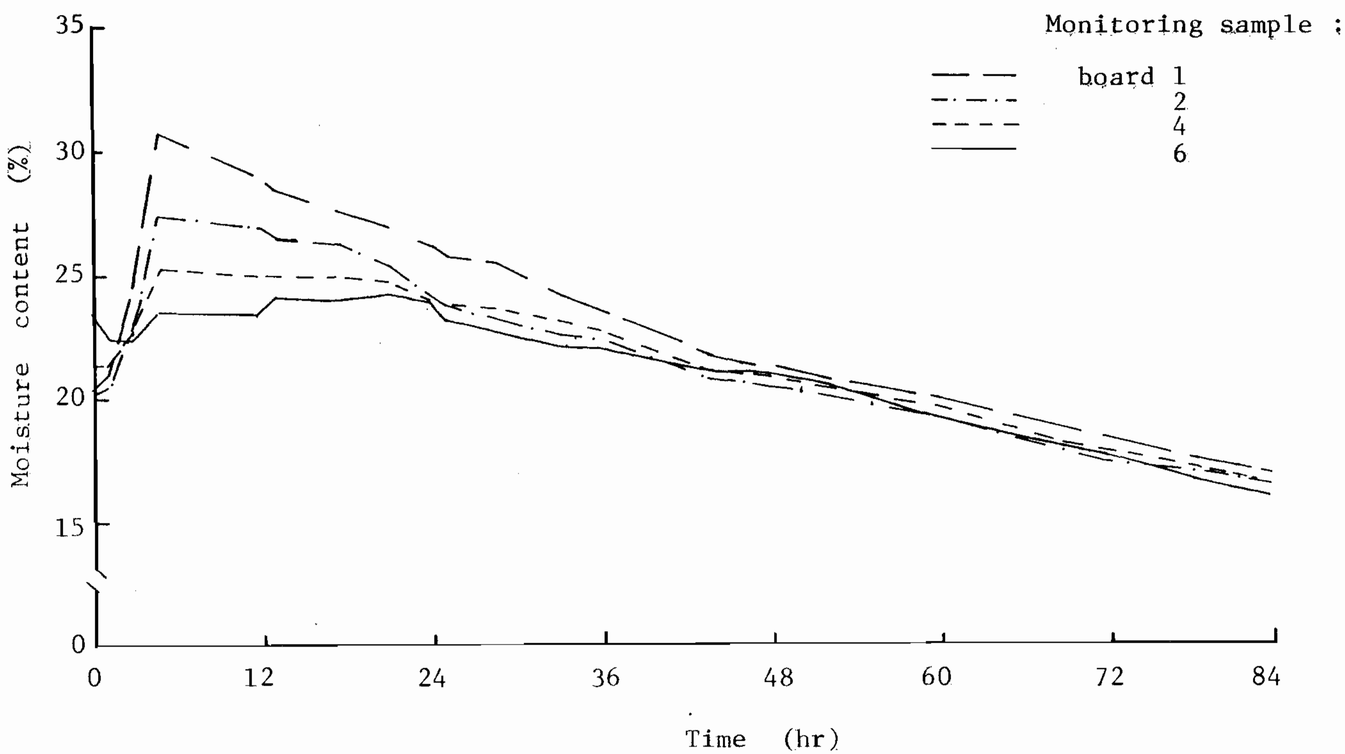

Fig. 27. Moisture distribution across a lumber stack monitored in four sample boards by the thermo-moisture meter.

was not so critical to the moisture gradient pattern that developed after the warm-up period because, as shown in Fig. 27, the order of the initial MCs of the four boards totally reversed after 3 to 4 hours into the run.

After the warm-up period, a distinctive moisture gradient developed across the the stack. Board 6 placed on the left edge of the package where the air entered the stack during the first drying step became the driest regardless of its highest initial MC. With the second step in the kiln schedule, the air direction was reversed and the drying rates of the monitored boards diminished. Especially, board 6 absorbed moisture at the beginning of and retained it throughout the second step. Air traveling across the stack must have carried enough moisture to slightly rewet board 6.

Fig. 28 shows how moisture gradients across the stack changed with changes in the direction of air flow and kiln conditions: the greatest moisture gradient occurred at 12 hours when the MC difference between board 1 and board 6 was 5.4 %. From then on, the moisture gradients were reduced and after 84 hours, the boards seemed close to an equilibrium with only 0.9 % MC difference between board 1 and board 6. The air direction plays more of a role in developing moisture gradients across a stack during the early stages of drying than later on.

Table 16 also indicates how the air direction influences the drying rate of lumber. During the first drying step, board 6 dried five times faster than the board 1 and four times faster than the

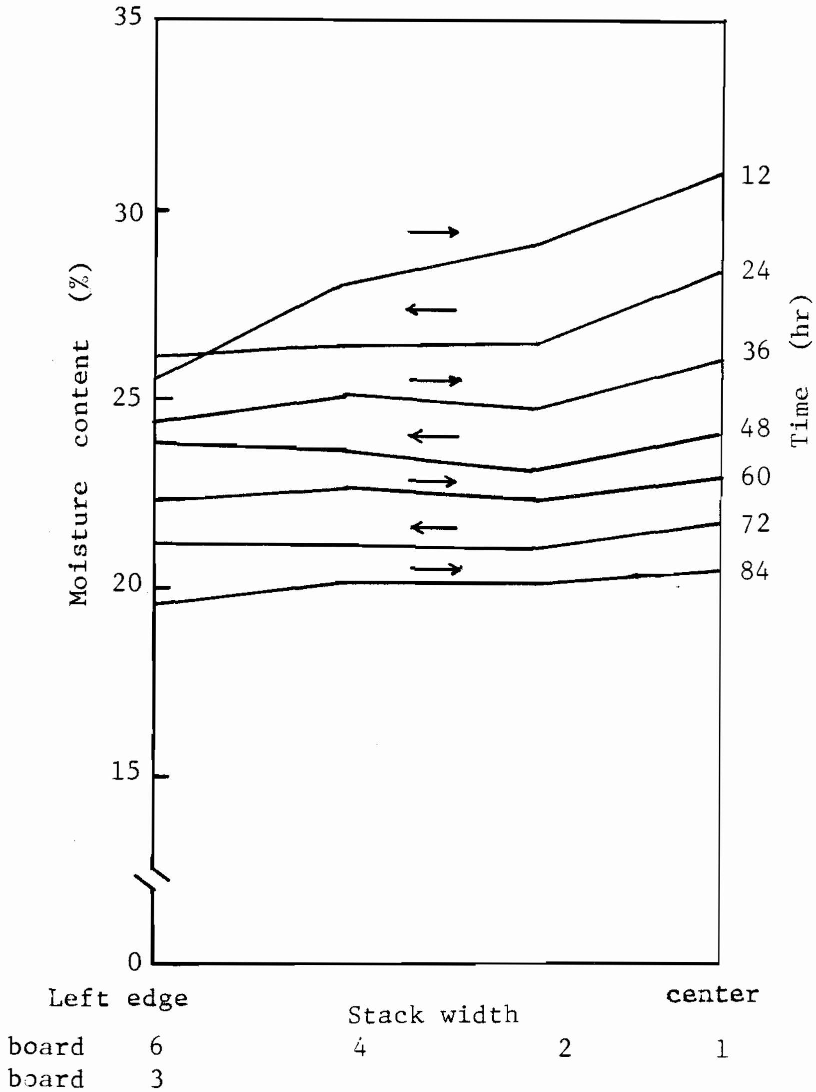

Fig. 28. Air flow directions across a stack of lumber and corresponding moisture gradients monitored with sample boards at the end of each drying step.

Table 16. Average drying rate (%MC/hr) during each 12 hours, based on the monitored MCs by the thermo-moisture meter.

Drying time (hr)	Sample board No. 1	2	4	6	Air direction
12	-0.258	-0.292	-0.858	(-1.300)	←
24	(-0.208)	-0.200	-0.050	+0.042 *	→
36	(-0.208)	-0.158	-0.117	-0.142	←
48	(-0.167)	-0.125	-0.117	-0.050	→
60	-0.092	-0.075	-0.083	(-0.125)	←
72	-0.092	-0.108	(-0.133)	-0.100	→
84	-0.108	-0.075	-0.083	(-0.125)	←

( ) : The largest drying rate in each drying step.
* : Adsorption.

board 2. The board on the air inlet side always dried the fastest except in two instances.

2) Prediction by the Simulation

As expected, the first simulated drying rates did not fit well to the initial RILRAT (real drying rates) averaged for boards 3 and 5, hence adjustments were made using Eqs. 7 and 8. The procedure is presented in Table 17. After the first adjustment, drying rate values (S2) again did not fully coincide with RO (initial RILRAT) values (Fig.29). However, a second iteration fitted the simulated drying curve well to the curve of real average MC versus time (Fig. 30). In this plot, the simulated values are the averages of MCs of two boards located at the edges of two side by side stacks.

From the final KILDRY output (Appendix E), drying time (TIME) and average MC of the current profile for the step (CBAR-P) were taken and the first four simulation positions with the four monitored boards 1, 2, 4, and 6 were plotted (Fig. 31). After the short period of condensation that is part of the simulation program, the moisture gradients between positions increased until around 12 hours reaching a maximum. For the next drying step, the air direction was changed and thereafter the simulated MC values increased slightly (Fig. 27).

Because the MC values of sample boards 3 and 5, were obtained directly and accurately by weighing, it was of interest to compare them to their simulated counterparts.

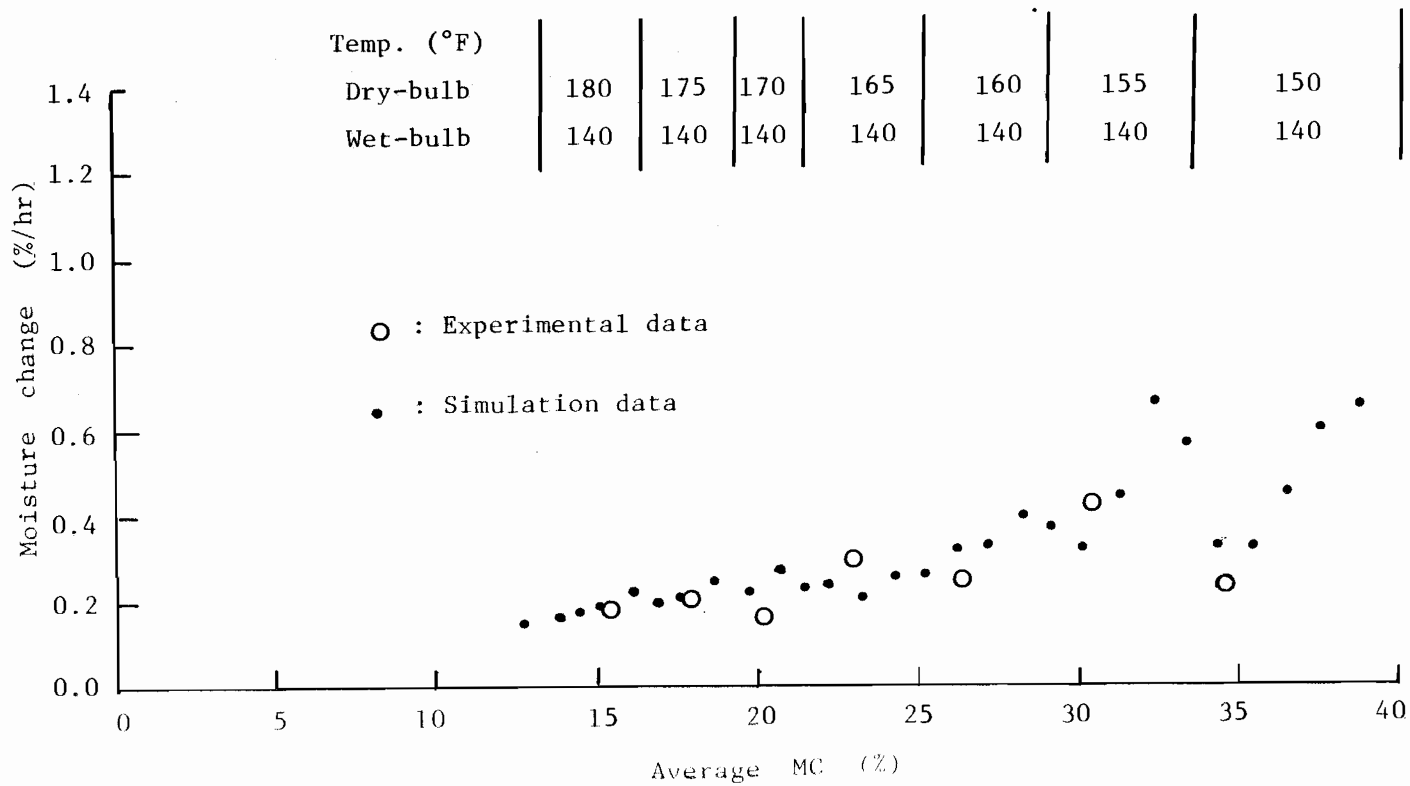

Fig. 29. Drying rate versus average MC: Last adjusted computer simulation data and actual average of two edge boards dried in the industrial kiln.

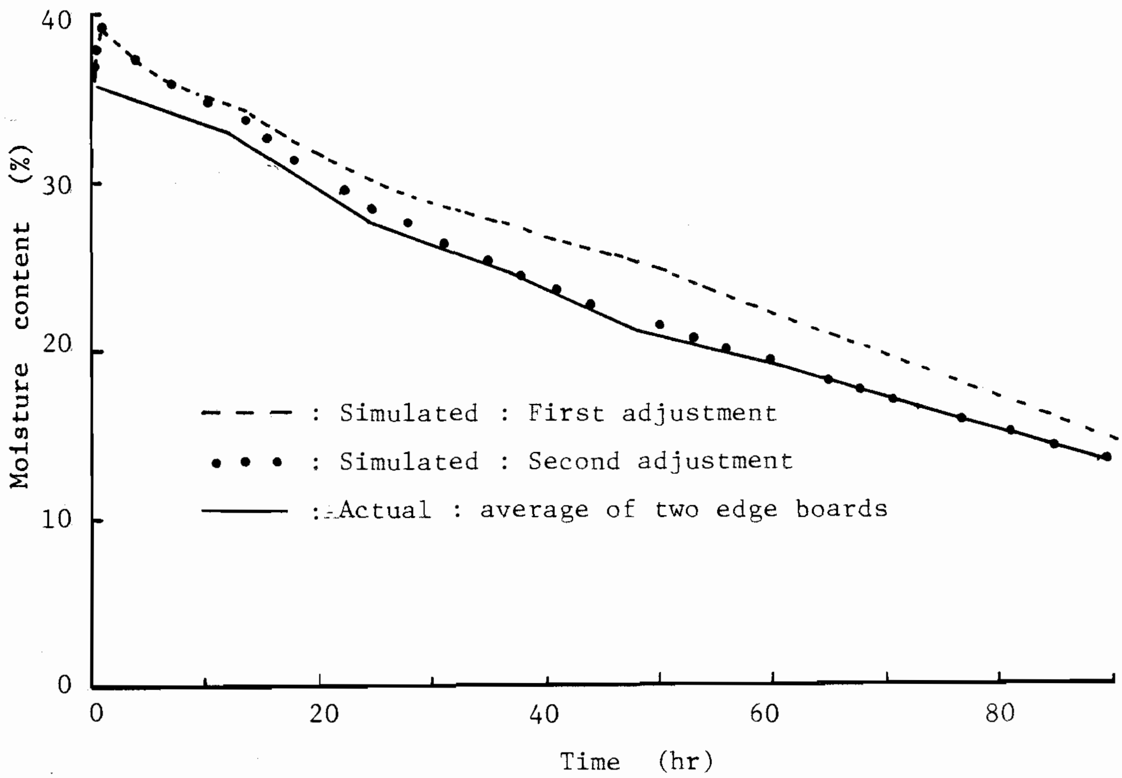

Fig. 30. Simulated and actual drying curves of the industrial kiln run.

Table 17. Progressive adjustments of drying rates obtained from the industrial kiln run.

CZR (%)	R0 (%/hr)	S0 (%/hr)	R1 (%/hr)	S1 (%/hr)	R2 (%/hr)	S2 (%/hr)
34.47	-0.242	-0.2113	-0.277	-0.1818	-0.369	-0.2009
30.44	-0.431	-0.4381	-0.4240	-0.2679	-0.682	-0.4232
26.36	-0.250	-0.3130	-0.200	-0.2069	-0.242	-0.3061
23.02	-0.306	-0.1346	-0.696	-0.2601	-0.819	-0.2348
20.16	-0.170	-0.1088	-0.266	-0.2627	-0.172	-0.2465
17.88	-0.210	-0.1639	-0.269	-0.2601	-0.217	-0.2245
15.49	-0.188	-0.1480	-0.239	-0.2557	-0.176	-0.2023

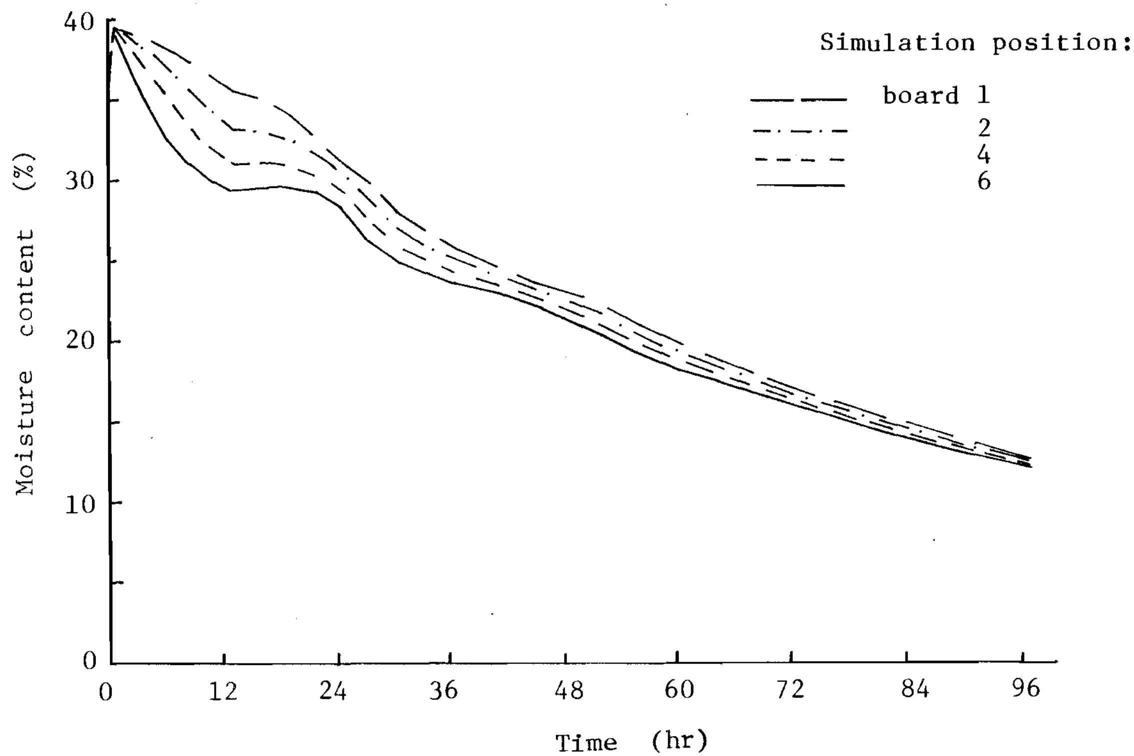

Fig. 31. Simulated moisture distribution between boards in the industrial kiln run.

Table 18 presents this comparison of the simulated and actually obtained MCs of the two boards located on either side of the kiln charge. The KILDRY simulation program assumed that both sample boards had the same initial MC values equal to their average initial MC. Therefore, the differences of the initial MC values were inevitable. Nevertheless, most steps showed a difference of less than 0.5%.

3) Comparing Observed and Simulated Results

In comparing moisture content values obtained with the thermo-moisture meter with those predicted by computer simulation, caution must be taken. Temperature effects on monitored moisture values must be removed. Furthermore, resistance type moisture meters are not very accurate above FSP.

Moisture content values calculated by the simulation program for positions, each of them corresponding to a monitored sample board, and monitored average MCs of the edge boards were assumed to be equal to each other. The simulated moisture values at stack edges were compared with the actual moisture values in Table 18.

Fig. 32. shows that the simulated moisture values were generally higher than the monitored moisture values during the first stages of drying, especially in the middle of stack. After 48 hr, when the boards became more uniform in moisture content,the simulated and monitored moisture values approached each other. However, at the end of the run, the simulated MCs were much lower.

In addition to Fig. 32, the monitored moisture distribution

Table 18. Comparison of simulated and actually determined moisture contents of two sample boards located on both sides of the industrial kiln charge.

Drying time	Average*	Board 3			Board 5		
		Predicted	Actual	Diff.	predicted	Actual	Diff.
(hr)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
0	35.9	35.9	34.5	1.4	35.9	37.4	-1.5
12	33.0	29.5	28.2	1.3	36.5	37.9	-1.4
24	27.8	26.6	26.9	-0.3	28.3	28.8	0.1
36	24.8	23.7	22.7	1.0	25.9	27.1	-1.2
48	21.1	20.4	20.5	-0.1	21.9	21.8	0.1
60	19.1	18.3	18.2	0.1	19.9	20.1	-0.2
72	16.6	16.3	16.7	-0.4	16.9	16.6	0.3
84	14.3	13.9	13.7	0.2	14.3	15.0	-0.2

* : Average MC determined by weight, boards 3 and 5.

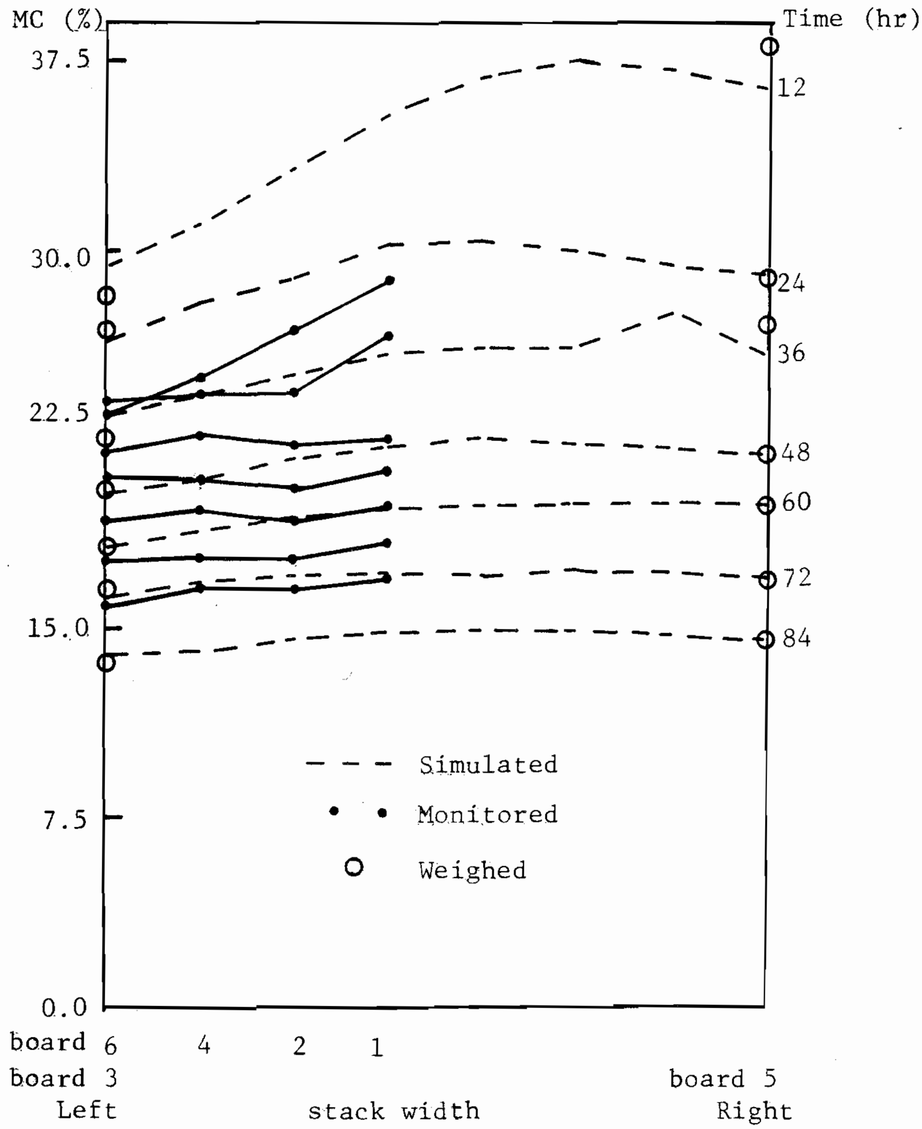

Fig. 32. Monitored and simulated moisture gradients in a stack

in Fig. 27 and the simulated moisture distribution in Fig. 31 could be used for comparison. Except at the very beginning of drying, plots of actual and simulated show drying curves of similar shape. After 12 hours when the first drying step was completed and fans reversed, maximum moisture gradients occurred across the stacks.

CONCLUSIONS

The analysis of research results permits the following conclusions.

1. The thermo-moisture meter made by J. Forrer was useful in continuously measuring moisture gradients and temperatures in wood. However, MC values monitored by the thermo-moisture meter must be corrected for the effect of wood temperatures. In meters to be manufactured in the future, such corrections could be preprogrammed, provided correction factors can be obtained for the various species to be dried.

2. The newly developed probes for the thermo-moisture meter appeared to monitor well D.C. resistances and temperatures at several layers within boards. However, electrodes placed just below the surfaces of boards become exposed to air as the wood shrinks during drying. This may lead to inaccuracies.

3. The kiln schedule used in this research caused stress reversals of 2-inch thick Douglas-fir heartwood boards starting at 48 hours and lasting until 72 hours of drying. In terms of MC, most sample boards had stress reversals between 15%-17% MC. This must be considered in any future modification of the schedule.

4. The monitored moisture gradients did not provide specific indications when stress reversal took place.

5. The first outputs of Hart's computer simulation did not

immediately show good agreement with the observed data. This may have been caused by inputting relatively inaccurate drying rates, because they were determined over relatively large intervals by weighing samples only every 12 hours. However, after two adjustments of the simulation input, the differences between simulated and observed MC values were not greater than + 0.5%. Also, most drying rates could be simulated to agree with the observed rates within $\pm$ 0.1% MC/hr.

6. Both, Hart's simulation programs and Forrer's thermo-moisture meter should be helpful in further studies of drying behavior and possible kiln schedule modification.

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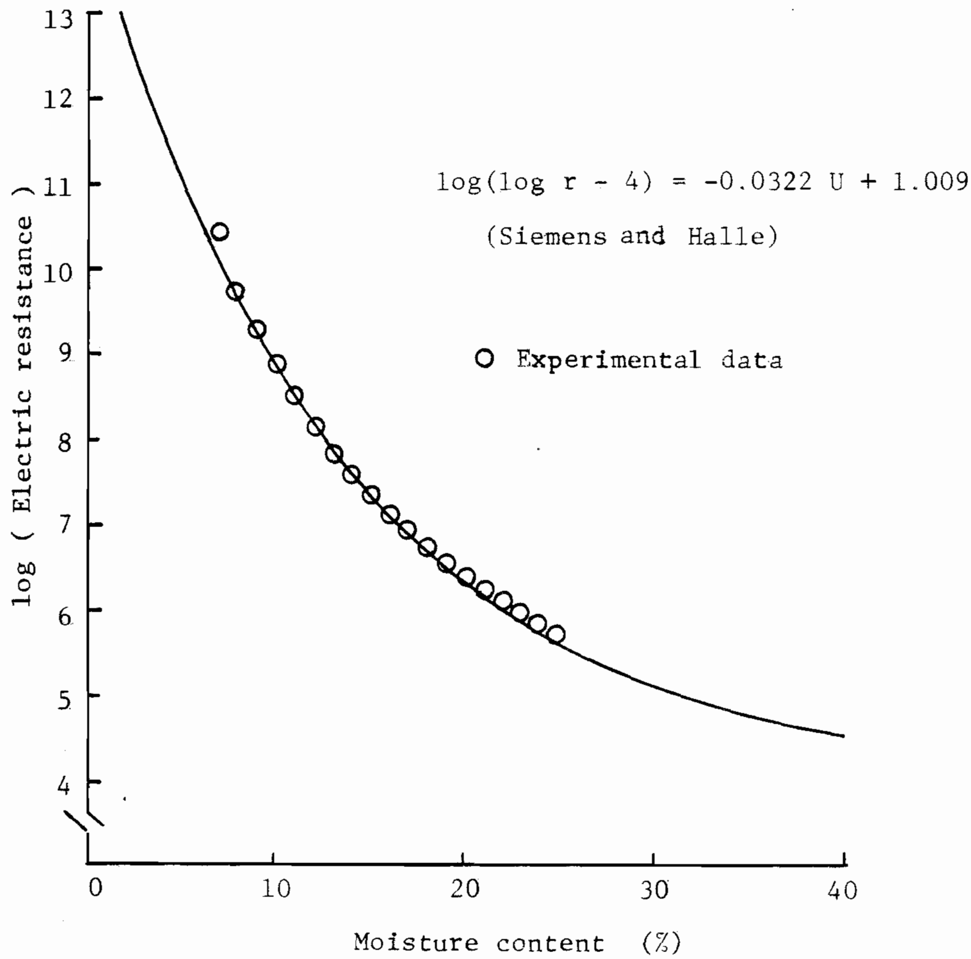
APPENDICES

Appendix A



Electric resistance versus MC of Douglas-fir: Experimentally determined relationship of D.C. electric resistance to MC for Douglas-fir (James 1963) shows good fit to Siemens and Halle's equation.

Appendix B

Specific gravity of Douglas-fir test samples

Oven-dry wt. (g)	Water displacement at 82 °F (g)	water volume at 82 °F (cm)	Specific gravity
108.4	220	220.8	0.49
74.9	214	214.8	0.35
96.7	207	207.8	0.47
101.5	231	231.9	0.44
76.9	189	189.7	0.41
113.7	242	242.9	0.47
110.4	250	250.9	0.44
100.9	223	223.8	0.45
91.7	218	218.8	0.42
106.0	230	230.9	0.46
81.5	188	188.7	0.43
91.7	208	208.8	0.44
		Average	0.44

Appendix C

Moisture content (%) of boards dried in the industrial kiln

Drying time (hr)	Sample board number 1	2	3*	4	5*	6
0	34.1	32.5	34.5	37.4	37.4	41.2
12			28.2		37.9	
24			26.9		28.8	
36			22.7		27.1	
48			20.5		21.8	
60			18.2		20.1	
72			16.7		16.6	
84			13.7		15.0	

* : MCs of boards 3 and 5 were determined by weighing every 12 hours. The other boards were monitored by the thermo-moisture meter .

Appendix D

Important input variables for Hart's simulation programs

A	Specimen half thickness (cm)
AIRSP	Air velocity (feet/hr)
B	Barometric pressure (psi)
cz	MC at which the diffusion coefficient multipliers applies (%MC)
CZR	Average MC at which the actual drying rate as input applied (%MC)
DZT	Diffusion coefficient (cm^2/hr)
FZ	Diffusion coefficient multiplier at spcially selected MC
FANTIM	Elapsed time since the last fan reversal (hr)
FANST	Total ellapsed time before each fan reversal (hr)
FINISH	Difference between average profile MC and EMC which terminates the computer run (%MC)
IRFLOW	Airflow direction 1 : Initial air flow is front to back -1 : Initial air flow is back to front
N	Number of cells in the moisture profile (30 max.)
NPAS	Number of positions across the stack
NSBC	Number of controlling sample board: A code designating the positions where moisture profiles are monitored to control the sorption schedule.
QRATES	Surface transfer coefficient ($g\ cm^{-2}\ hr^{-1}\ {}^{\circ}F^{-1}$)
RAE	Relative Activation Energy
RILRAT(I)	Sorption rate of the real data (%MC/hr)
SG	Specific gravity (oven-dry weight/initial volume)
STT	Sticker thickness (inches)

TZD	Temperature at which DZT is defined (°F)
TZQS	Temperature at which QRATES is defined (°F)
TDL	Temperature-dependent-limit (%MC)
TW	Temperature of wood (°F)
TWDLT	Maximum permissible wood temperature change per program loop.
WID	Effective width of stack, omitting gaps (feet)
WRT	Write interval for print-out (%MC or hr)

APPENDIX E

Computer Simulation Output

Table E1. Output of the KILSOR simulation using average moisture contents of each step in kiln run 1.

```
             1     KILSOR  UM DATA, DOUGLAS-FIR 1984  JULY  ADJ  2  A  T=HR    0
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)   TWBS(I)  NSO(I)      TEST(I)      QRATES(I)    TZQS(I)   AIRSP(I)     NS        ROB       EMC                                J      NPL
     (F)       (F)             (T OR %MC)   (G/CM2 T F)      (F)       (FT/T)                         (%MC)
0  CBARP        TIME   CBARAV     AVRATE     TDB  TDB-EX      TW     RW    K   DELTEF S
*                                                                                      %MC 1   %MC 4   %MC 7   %MC10   %MC13   %MC14   %MC20   %MC24
   (%MC)        (T)    (%MC)    (%MC/T)     (F)     (F)     (F)                 (%)
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)   TWBS(I)  NSO(I)      TEST(I)      QRATES(I)    TZQS(I)   AIRSP(I)     NS        ROB       EMC                                J      NPL
  150 0000  140 0000      -1      26 9200      2442E-02    122 4000   2400E+05     1         762     12 46                                2        1
0  CBARP        TIME   CBARAV     AVRATE     TDB  TDB-EX      TW     RW    K   DELTEF S
*                                                                                      %MC 1   %MC 4   %MC 7   %MC10   %MC13   %MC14   %MC20   %MC24
   32 63 0              32 830 0               150 00  150 00   80 00                  32 63   32 63   32 63   32 63   32 63   32 63   32 63   32 63
   33 66    1746E-01    33 144    5664E+02  126 26  118 51   99 69  1 000    2    2 739  56 96   32 63   32 63   32 63   32 63   32 63   32 63   32 63
   34 75    4296E-01    34 205    4298E+02  137 12  129 70  119 51  1 000    3    5 923  60 97   32 63   32 63   32 63   32 63   32 63   32 63   32 63
   35 60    1554E+00    35 277    9310E+01  145 63  142 96  139 43  1 000    4   30 606  65 04   33 66   32 63   32 63   32 63   32 63   32 63   32 63
   34 74    6703E+00    35 272 -  1479E+01  146 06  143 35  140 01  1 000    5  100 000  40 22   40 62   34 91   32 92   32 65   32 64   32 63   32 63
   33 66    1584E+01    34 210 -  1495E+01  146 17  143 51  140 25    993    6  100 000  26 67   37 17   35 94   33 62   32 69   32 77   32 63   32 63
   32 64    2349E+01    33 156 -  1356E+01  146 52  144 10  141 13    966    7  100 000  22 67   32 96   34 94   34 20   33 27   33 07   32 65   32 63
   31 64    3216E+01    32 136 -  1155E+01  147 04  144 99  142 47    933    8  100 000  19 45   29 26   33 01   33 79   33 44   33 28   32 72   32 65
   30 61    4342E+01    31 122 -  9166E+00  147 72  146 14  144 20    890    9  100 000  16 94   26 24   30 56   32 60   33 14   33 15   32 62   32 72
   29 56    5619E+01    30 092 -  6963E+00  148 32  147 15  145 71    855   10  100 000  15 41   24 19   28 26   30 90   32 24   32 46   32 65   32 61
   28 57    7695E+01    29 076 -  5345E+00  148 72  147 63  146 74    831   11  100 000  14 57   22 62   26 47   29 16   30 97   31 39   32 61   32 76
   27 57    1007E+02    28 070 -  4239E+00  148 99  148 28  147 42    816   12  100 000  14 07   21 79   25 12   27 66   29 61   30 12   31 96   32 33
   26 91    1191E+02    27 237 -  3569E+00  149 11  148 49  147 73    610   13  100 000  13 66   21 26   24 43   26 63   28 75   29 29   31 36   31 79
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)   TWBS(I)  NSO(I)      TEST(I)      QRATES(I)    TZQS(I)   AIRSP(I)     NS        ROB       EMC                                J      NPL
  155 0000  140 0000      -1      22 6600      2442E-02    122 4000   2400E+05     2         667     10 25                              230       26
0  CBARP        TIME   CBARAV     AVRATE     TDB  TDB-EX      TW     RW    K   DELTEF S
*                                                                                      %MC 1   %MC 4   %MC 7   %MC10   %MC13   %MC14   %MC20   %MC24
   25 90    1399E+02    26 405 -  4622E+00  153 65  153 08  152 10    720   14  100 000  11 44   20 09   23 63   25 99   27 66   28 42   30 56   31 03
   24 90    1661E+02    25 401 -  3632E+00  154 06  153 40  152 61    711   15  100 000  11 21   18 97   22 66   25 01   26 65   27 37   29 53   30 01
   23 69    1965E+02    24 394 -  3335E+00  154 16  153 61  152 92    705   16  100 000  11 06   18 01   21 75   24 07   25 76   26 27   28 34   28 60
   22 66    2310E+02    23 362 -  2926E+00  154 27  153 76  153 15    700   17  100 000  10 96   16 97   20 65   23 15   24 75   25 19   27 07   27 50
   22 66    2362E+02    22 776 -  2734E+00  154 29  153 79  153 19    700   18  100 000  10 96   16 77   20 66   22 96   24 56   24 99   26 62   27 24
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)   TWBS(I)  NSO(I)      TEST(I)      QRATES(I)    TZQS(I)   AIRSP(I)     NS        ROB       EMC                                J      NPL
  160 0000  140 0000      -1      19 2600      2442E-02    122 4000   2400E+05     3         565      6 64                              477       29
0  CBARP        TIME   CBARAV     AVRATE     TDB  TDB-EX      TW     RW    K   DELTEF S
*                                                                                      %MC 1   %MC 4   %MC 7   %MC10   %MC13   %MC14   %MC20   %MC24
   21 67    2665E+02    22 174 -  3566E+00  159 17  156 59  157 91    616   19  100 000   9 26   15 31   19 77   22 16   23 76   24 16   25 64   26 22
   20 67    3019E+02    21 166 -  2632E+00  159 30  156 61  156 24    613   20  100 000   9 16   14 32   16 62   21 15   22 76   23 17   24 74   25 07
   19 66    3433E+02    20 164 -  2426E+00  159 40  156 96  156 46    609   21  100 000   9 09   13 60   17 36   20 06   21 66   22 09   23 60   23 91
   19 26    3609E+02    19 469 -  2196E+00  159 43  159 03  156 56    606   22  100 000   9 06   13 35   16 63   19 63   21 25   21 66   23 16   23 47
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)   TWBS(I)  NSO(I)      TEST(I)      QRATES(I)    TZQS(I)   AIRSP(I)     NS        ROB       EMC                                J      NPL
  165 0000  140 0000      -1      16 6000      2442E-02    122 4000   2400E+05     4         515      7 40                              746       35
0  CBARP        TIME   CBARAV     AVRATE     TDB  TDB-EX      TW     RW    K   DELTEF S
*                                                                                      %MC 1   %MC 4   %MC 7   %MC10   %MC13   %MC14   %MC20   %MC24
   18 27    3981E+02    18 775 -  2690E+00  164 37  163 93  163 42    536   23  100 000   7 76   12 39   15 62   16 60   20 33   20 75   22 25   22 55
   17 27    4457E+02    17 770 -  2120E+00  164 47  164 10  163 67    533   24  100 000   7 70   11 77   14 49   17 14   19 16   19 61   21 19   21 49
   16 60    4619E+02    16 931 -  1651E+00  164 52  164 19  163 60    531   25  100 000   7 67   11 42   13 67   16 22   16 29   16 76   20 44   20 76
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)   TWBS(I)  NSO(I)      TEST(I)      QRATES(I)    TZQS(I)   AIRSP(I)     NS        ROB       EMC                                J      NPL
  170 0000  140 0000      -1      14 0600      2442E-02    122 4000   2400E+05     5         454      6 39                              973       52
0  CBARP        TIME   CBARAV     AVRATE     TDB  TDB-EX      TW     RW    K   DELTEF S
*                                                                                      %MC 1   %MC 4   %MC 7   %MC10   %MC13   %MC14   %MC20   %MC24
   15 56    5269E+02    16 090 -  2153E+00  169 46  169 13  168 71    469   26  100 000   6 63   10 54   12 96   15 11   17 03   17 59   19 46   19 61
   14 57    5662E+02    15 076 -  1706E+00  169 56  169 26  168 91    466   27  100 000   6 60    9 97   12 20   14 01   15 67   16 17   16 29   16 69
   14 07    6214E+02    14 322 -  1507E+00  169 60  169 32  168 99    465   28  100 000   6 56    9 73   11 64   13 53   15 06   15 52   17 59   18 06
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)   TWBS(I)  NSO(I)      TEST(I)      QRATES(I)    TZQS(I)   AIRSP(I)     NS        ROB       EMC                                J      NPL
  175 0000  140 0000      -1      12 1900      2442E-02    122 4000   2400E+05     6         401      5 57                             1173       72
0  CBARP        TIME   CBARAV     AVRATE     TDB  TDB-EX      TW     RW    K   DELTEF S
*                                                                                      %MC 1   %MC 4   %MC 7   %MC10   %MC13   %MC14   %MC20   %MC24
   13 07    6779E+02    13 572 -  1771E+00  174 56  174 27  173 92    411   29  100 000   5 73    8 66   11 05   12 72   14 06   14 50   16 37   16 63
   12 19    7407E+02    12 629 -  1409E+00  174 63  174 37  174 06    410   30  100 000   5 71    8 36   10 37   11 92   13 14   13 49   15 09   15 46
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)   TWBS(I)  NSO(I)      TEST(I)      QRATES(I)    TZQS(I)   AIRSP(I)     NS        ROB       EMC                                J      NPL
  180 0000  140 0000      -1       5 1600      2442E-02    122 4000   2400E+05     7         354      4 67                             1344       76
0  CBARP        TIME   CBARAV     AVRATE     TDB  TDB-EX      TW     RW    K   DELTEF S
*                                                                                      %MC 1   %MC 4   %MC 7   %MC10   %MC13   %MC14   %MC20   %MC24
   11 16    8051E+02    11 665 -  1555E+00  179 61  179 34  179 04    363   31  100 000   4 99    7 53    9 51   11 04   12 21   12 53   13 65   14 17
   10 16    8892E+02    10 661 -  1197E+00  179 66  179 46  179 22    361   32  100 000   4 97    7 01    8 65   10 02   11 07   11 36   12 49   12 74
    9 16    9945E+02     9 677 -  9520E-01  179 75  179 57  179 36    360   33  100 000   4 95    6 54    7 63    8 96    9 90   10 15   11 14   11 36
    8 17    1133E+03     8 674 -  7287E-01  179 81  179 66  179 53    356   34  100 000   4 93    6 11    7 07    7 94    8 69    8 90    9 76    9 95
    7 17    1325E+03     7 671 -  5202E-01  179 87  179 77  179 67    357   35  100 000   4 91    5 72    6 36    6 99    7 51    7 66    8 31    8 46
0                                                                                                                                      J      NPL
                                                                                                                                    2202      114
```

Table E2. Output of the KILSOR simulation using moisture contents of the monitoring sample board in kiln run 1.

```
           1     KILSOR  UM DATA, DOUGLAS-FIR 1984   JULY  ADJ   2   S   T=HR     0
0*-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)     TZQS(I)    AIRSP(I)       NS        RDB         EMC                              J      NPL
       (F)        (F)           (T OR XMC)   (G/CM2 T F)          (F)      (FT/T)                              (XMC)
0  CBARP         TIME  CBARAV       AVRATE     TDB  TDB-EX       TW     RW   K   DELTEF S
*                                                                                    XMC 1   XMC 4   XMC 7   XMC10   XMC13   XMC14   XMC20   XMC24
   (XMC)          (T)   (XMC)      (XMC/T)      (F)    (F)       (F)                  (X)

0*-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)     TZQS(I)    AIRSP(I)       NS        RDB         EMC                              J      NPL
  150.0000   140.0000      -1       29.4900      .2442E-02    122.4000   2400E+05        1        .762       12.46                              2        1
0  CBARP         TIME  CBARAV       AVRATE     TDB  TDB-EX       TW     RW   K   DELTEF S
*                                                                                    XMC 1   XMC 4   XMC 7   XMC10   XMC13   XMC14   XMC20   XMC24
   34.90 0.             34.900 0.              150.00 150.00   60.00                      34.90   34.90   34.90   34.90   34.90   34.90   34.90   34.90
   35.97    .1611E-01   35.433     .5663E+02 126.28 116.51   99.69  1.000   2    1.646   60.26   34.90   34.90   34.90   34.90   34.90   34.90   34.90
   37.10    .4454E-01   36.533     .4296E+02 137.12 129.70  119.51  1.000   3    3.969   65.87   34.90   34.90   34.90   34.90   34.90   34.90   34.90
   36.19    .1610E+00   37.643     .9313E+01 145.63 142.96  139.43  1.000   4   20.727   95.26   35.34   34.90   34.90   34.90   34.90   34.90   34.90
   37.10    .6945E+00   37.643 -   .1461E+01 148.06 143.34  140.00  1.000   5  100.000   45.69   42.61   36.05   34.96   34.90   34.90   34.90   34.90
   35.99    .1627E+01   36.546 -   .1513E+01 146.13 143.43  140.14   .996   6  100.000   30.95   40.76   37.56   35.44   34.96   34.92   34.90   34.90
   34.93    .2402E+01   35.460 -   .1372E+01 146.49 144.04  141.05   .970   7  100.000   23.13   36.74   37.53   35.96   35.15   35.04   34.90   34.90
   33.67    .3347E+01   34.396 -   .1121E+01 147.15 145.16  142.73   .926   8  100.000   16.99   32.36   36.12   36.09   35.40   35.24   34.92   34.90
   32.63    .4466E+01   33.351 -   .9256E+00 147.67 146.05  144.07   .694   9  100.000   17.11   26.47   33.69   35.46   35.46   35.36   34.96   34.91
   31.61    .5790E+01   32.321 -   .7741E+00 146.06 146.75  145.11   .669  10  100.000   15.86   25.23   31.37   34.23   35.11   35.17   35.01   34.95
   30.76    .7449E+01   31.294 -   .6196E+00 146.50 147.45  146.17   .644  11  100.000   15.03   23.04   26.62   32.46   34.24   34.54   35.02   34.99
   29.76    .9477E+01   30.269 -   .5046E+00 146.76 147.93  146.89   .626  12  100.000   14.46   21.64   26.61   30.56   32.97   33.49   34.64   34.97
   29.47    .1012E+02   29.613 -   .4452E+00 146.65 146.05  147.07   .624  13  100.000   14.33   21.35   26.07   30.03   32.56   33.13   34.74   34.93
0*-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)     TZQS(I)    AIRSP(I)       NS        RDB         EMC                              J      NPL
  155.0000   140.0000      -1       25.2100      .2442E-02    122.4000   2400E+05        2        .667       10.25                            158       30
0  CBARP         TIME  CBARAV       AVRATE     TDB  TDB-EX       TW     RW   K   DELTEF S
*                                                                                    XMC 1   XMC 4   XMC 7   XMC10   XMC13   XMC14   XMC20   XMC24
   28.45    .1203E+02   26.959 -   .5367E+00 153.76 152.69  151.85   .725  14  100.000   11.55   20.30   24.63   26.57   31.37   32.06   34.32   34.68
   27.44    .1453E+02   27.943 -   .4030E+00 154.02 153.35  152.53   .712  15  100.000   11.25   19.70   23.35   26.95   29.91   30.69   33.55   34.09
   26.43    .1749E+02   26.934 -   .3415E+00 154.16 153.56  152.67   .706  16  100.000   11.10   19.29   22.42   25.56   28.46   29.27   32.46   33.13
   25.42    .2066E+02   25.926 -   .2961E+00 154.27 153.76  153.14   .701  17  100.000   10.99   18.93   21.72   24.47   27.10   27.89   31.14   31.86
   25.21    .2165E+02   25.315 -   .2756E+00 154.29 153.79  153.19   .700  18  100.000   10.96   18.66   21.59   24.26   26.82   27.60   30.83   31.55
0*-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)     TZQS(I)    AIRSP(I)       NS        RDB         EMC                              J      NPL
  160.0000   140.0000      -1       21.6500      .2442E-02    122.4000   2400E+05        3        .565        6.64                            357       33
0  CBARP         TIME  CBARAV       AVRATE     TDB  TDB-EX       TW     RW   K   DELTEF S
*                                                                                    XMC 1   XMC 4   XMC 7   XMC10   XMC13   XMC14   XMC20   XMC24
   24.20    .2491E+02   24.701 -   .3091E+00 159.26 158.79  156.20   .613  19  100.000    9.17   16.49   21.02   23.41   25.69   26.40   29.49   30.19
   23.19    .2694E+02   23.693 -   .2505E+00 159.38 158.95  158.44   .610  20  100.000    9.10   16.19   20.51   22.56   24.51   25.12   27.91   28.57
   22.19    .3354E+02   22.666 -   .2161E+00 159.46 159.09  156.64   .606  21  100.000    9.04   17.90   20.04   21.76   23.40   23.91   26.25   26.83
   21.65    .3632E+02   21.916 -   .1943E+00 159.50 159.16  156.75   .605  22  100.000    9.00   17.74   19.79   21.35   22.82   23.27   25.35   25.86
0*-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-

0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)     TZQS(I)    AIRSP(I)       NS        RDB         EMC                              J      NPL
  165.0000   140.0000      -1       18.9500      .2442E-02    122.4000   2400E+05        4        .515        7.40                            640       35
0  CBARP         TIME  CBARAV       AVRATE     TDB  TDB-EX       TW     RW   K   DELTEF S
*                                                                                    XMC 1   XMC 4   XMC 7   XMC10   XMC13   XMC14   XMC20   XMC24
   20.64    .3990E+02   21.143 -   .2609E+00 164.23 163.70  163.06   .541  23  100.000    7.64   16.67   19.26   20.76   22.07   22.47   24.24   24.67
   19.63    .4401E+02   20.136 -   .2446E+00 164.37 163.93  163.42   .536  24  100.000    7.76   15.64   16.51   20.04   21.20   21.55   23.08   23.45
   16.94    .4730E+02   19.289 -   .2095E+00 164.49 164.13  163.71   .532  25  100.000    7.69   14.90   16.01   19.52   20.57   20.88   22.24   22.57
0*-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)     TZQS(I)    AIRSP(I)       NS        RDB         EMC                              J      NPL
  170.0000   140.0000      -1       16.2400      .2442E-02    122.4000   2400E+05        5        .454        6.39                            870       38
0  CBARP         TIME  CBARAV       AVRATE     TDB  TDB-EX       TW     RW   K   DELTEF S
*                                                                                    XMC 1   XMC 4   XMC 7   XMC10   XMC13   XMC14   XMC20   XMC24
   17.94    .5143E+02   18.444 -   .2423E+00 169.42 169.02  168.55   .471  26  100.000    6.66   11.76   17.21   18.81   19.64   20.11   21.24   21.51
   16.94    .5665E+02   17.441 -   .1923E+00 169.52 169.16  166.79   .466  27  100.000    6.62   10.78   16.11   17.93   18.96   19.22   20.19   20.39
   16.24    .6066E+02   16.589 -   .1665E+00 169.57 169.27  166.92   .466  28  100.000    6.59   10.27   15.02   17.25   16.31   16.57   19.50   19.68
0*-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)     TZQS(I)    AIRSP(I)       NS        RDB         EMC                              J      NPL
  175.0000   140.0000      -1       14.2500      .2442E-02    122.4000   2400E+05        6        .401        5.57                           1175       45
0  CBARP         TIME  CBARAV       AVRATE     TDB  TDB-EX       TW     RW   K   DELTEF S
*                                                                                    XMC 1   XMC 4   XMC 7   XMC10   XMC13   XMC14   XMC20   XMC24
   15.23    .6620E+02   15.736 -   .1881E+00 174.54 174.23  173.87   .412  29  100.000    5.74    9.29   12.51   16.26   17.50   17.77   18.71   18.89
   14.25    .7265E+02   14.741 -   .1486E+00 174.62 174.36  174.05   .410  30  100.000    5.71    6.68   11.11   14.41   16.52   16.85   17.88   18.07
0*-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)     TZQS(I)    AIRSP(I)       NS        RDB         EMC                              J      NPL
  180.0000   140.0000      -1        5.1600      .2442E-02    122.4000   2400E+05        7        .354        4.67                           1397       70
0  CBARP         TIME  CBARAV       AVRATE     TDB  TDB-EX       TW     RW   K   DELTEF S
*                                                                                    XMC 1   XMC 4   XMC 7   XMC10   XMC13   XMC14   XMC20   XMC24
   13.24    .7909E+02   13.743 -   .1612E+00 179.60 179.33  179.02   .363  31  100.000    5.00    7.83   10.09   12.41   15.36   15.88   17.15   17.36
   12.24    .8694E+02   12.736 -   .1276E+00 179.66 179.43  179.17   .362  32  100.000    4.98    7.36    9.29   11.09   13.09   13.84   16.32   16.58
   11.23    .9626E+02   11.732 -   .1060E+00 179.71 179.51  179.29   .361  33  100.000    4.96    6.96    8.64   10.17   11.66   12.16   15.19   15.71
   10.23    .1072E+03   10.726 -   .9207E-01 179.75 179.56  179.38   .360  34  100.000    4.95    6.67    8.10    9.44   10.65   11.05   13.33   14.15
    9.22    .1200E+03    9.722 -   .7657E-01 179.76 179.64  179.47   .359  35  100.000    4.94    6.40    7.61    8.74    9.76   10.06   11.54   11.96
    8.22    .1354E+03    8.717 -   .6507E-01 179.62 179.70  179.57   .356  36  100.000    4.92    6.09    7.05    7.93    8.70    8.92    9.90   10.13
    7.21    .1558E+03    7.715 -   .4904E-01 179.87 179.79  179.69   .357  37  100.000    4.91    5.73    6.41    7.02    7.56    7.71    8.36    8.54
0                                                                                                                                             J      NPL
                                                                                                                                           2383      122
```

Table E3. Output of the KILDRY simulation using average moisture contents of the MC sample boards in the industrial kiln run.

```
            I     KILDRY4 UM DATA, DOUGLAS-FIR 1984  OCT    ADJ  2  A  T*HR    0
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)    TZQS(I)    AIRSP(I)       NS        RDB         EMC
       (F)        (F)           (T OR XMC)   (G/CM2 T F)       (F)        (FT/T)                               (XMC)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
0 IRFLOW     FANTIM         TIME    TDBS    TWBS               RDB        J              EMC             DELT
                (T)          (T)     (F)     (F)                                       (XMC)              (T)
0 CBAR-P     RATE-PK      CBAR-PK    TDB  TDB-EX       TW       RW        K  DELTEF
*                                                                                      XMC 1   XMC 2   XMC 3   XMC 4   XMC 5   XMC 6   XMC 8   XMC 9
    (XMC)     (XMC/T)       (XMC)    (F)     (F)      (F)                       (X)
0CBAR-AP    RATE-APK     CBAR-APK  TDB-EX                                NPL               CSBAV     RATE-SBK   CSBAV-K
    (XMC)     (XMC/T)       (XMC)    (F)                                                   (XMC)      (XMC/T)     (XMC)

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)    TZQS(I)    AIRSP(I)       NS        RDB         EMC
  150.0000   140.0000      -1       33.0200      .1875E-02   122.4000    .1200E+05       1        .782       12.48
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
0 IRFLOW     FANTIM         TIME    TDBS    TWBS               RDB        J              EMC             DELT
      1.0          0              150.00  140.00               .782       2            12.48     0.
0 CBAR-P     RATE-PK      CBAR-PK    TDB  TDB-EX       TW       RW        K  DELTEF
*                                                                                      XMC 1   XMC 2   XMC 3   XMC 4   XMC 5   XMC 6   XMC 8   XMC 9
  35.92 0                   35.92 150.00  150.00    75.00 * * *           1  * * *     35.92   35.92   35.92   35.92   35.92   35.92   35.92   35.92
0CBAR-AP    RATE-APK     CBAR-APK  TDB-EX                                NPL               CSBAV     RATE-SBK   CSBAV-K
  35.92                                                                                35.92

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
0 IRFLOW     FANTIM         TIME    TDBS    TWBS               RDB        J              EMC             DELT
      -1   .2227E+01    .1458E+02  150.00  140.00               .782      48            12.48        .4595E+00
0 CBAR-P     RATE-PK      CBAR-PK    TDB  TDB-EX       TW       RW        K  DELTEF
*                                                                                      XMC 1   XMC 2   XMC 3   XMC 4   XMC 5   XMC 6   XMC 8   XMC 9
  29.54 - .4382E+00         32.73 141.02  141.20   141.69     .955        2   53.03    21.28   24.28   28.35   28.58   30.62   32.28   34.29   34.68
  31.12 - .3297E+00         33.52 140.70  140.80   141.08     .971        2   53.03    23.30   25.82   28.05   30.37   32.38   33.89   35.53   35.81
  33.27 - .1817E+00         34.80 140.82  140.59   140.49     .988        2   53.03    28.44   28.95   31.09   33.11   34.85   35.88   36.58   36.70
  35.47 - .3078E-01         35.70 140.85  140.88   140.18     .995        2   53.03    30.44   32.98   34.57   35.84   36.85   37.07   37.25   37.24
  36.93   .8915E-01         36.42 141.43  141.07   140.07     .998        2   53.03    33.08   35.79   36.99   37.87   37.93   37.92   37.83   37.54
  37.51   .1090E+00         36.71 142.53  141.88   140.07     .998        2   53.03    33.14   36.95   38.21   38.85   38.83   38.39   37.84   37.70
  37.34   .9738E-01         36.83 144.49  143.33   140.18     .995        2   53.03    30.33   36.81   38.50   39.08   38.98   38.82   37.94   37.77
  36.45   .3839E-01         36.19 147.74  145.89   140.80     .977        2   53.03    24.38   34.78   38.00   39.05   39.07   38.72   37.98   37.81
0CBAR-AP    RATE-APK     CBAR-APK  TDB-EX                                NPL               CSBAV     RATE-SBK   CSBAV-K
  34.70 - .8355E-01         35.31 141.20                                 112               32.99   - .2009E+00    34.48

- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
0*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)    TZQS(I)    AIRSP(I)       NS        RDB         EMC
  155.0000   140.0000      -1       27.8500      .1675E-02   122.4000    .1200E+05       2        .887       10.25
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
0 IRFLOW     FANTIM         TIME    TDBS    TWBS               RDB        J              EMC             DELT
       1   .2472E+01    .2696E+02  155.00  140.00               .867      79            10.25       .4070E+00
0 CBAR-P     RATE-PK      CBAR-PK    TDB  TDB-EX       TW       RW        K  DELTEF
*                                                                                      XMC 1   XMC 2   XMC 3   XMC 4   XMC 5   XMC 6   XMC 8   XMC 9
  28.56 - .2401E+00         28.05 153.84  152.89   150.31     .754        3  100.00    12.33   22.48   25.48   27.48   28.85   29.82   30.98   31.19
  27.80 - .2677E+00         29.46 151.50  150.35   147.24     .818        3  100.00    14.18   23.38   26.34   28.48   29.99   31.07   32.34   32.59
  29.21 - .3280E+00         31.24 148.97  147.83   144.74     .875        3  100.00    16.29   24.24   27.29   29.59   31.30   32.55   33.97   34.24
  30.28 - .4208E+00         32.88 148.72  145.81   143.34     .909        3  100.00    17.94   24.73   27.77   30.27   32.24   33.70   35.33   35.83
  30.49 - .5191E+00         33.71 145.09  144.50   142.88     .921        3  100.00    18.82   24.57   27.47   30.10   32.30   34.00   35.93   36.29
  30.14 - .5943E+00         33.83 144.10  143.77   142.89     .921        3  100.00    18.82   24.10   26.80   29.43   31.74   33.80   35.82   36.24
  29.58 - .8278E+00         33.45 143.81  143.48   143.12     .915        3  100.00    18.27   23.57   26.18   28.70   31.00   32.91   35.30   35.77
  28.94 - .8082E+00         32.89 143.49  143.50   143.52     .908        3  100.00    17.72   23.07   25.88   28.08   30.31   32.20   34.83   35.11
0CBAR-AP    RATE-APK     CBAR-APK  TDB-EX                                NPL               CSBAV     RATE-SBK   CSBAV-K
  29.12 - .4505E+00         31.91 143.50                                 142               27.75   - .4232E+00    30.37

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0  TDBS(I)    TWBS(I)  NSD(I)       TEST(I)      QRATES(I)    TZQS(I)    AIRSP(I)       NS        RDB         EMC
  160.0000   140.0000      -1       24.8800      .1875E-02   122.4000    .1200E+05       3        .585        8.84
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
0 IRFLOW     FANTIM         TIME    TDBS    TWBS               RDB        J              EMC             DELT
       1   .1217E+02    .3885E+02  160.00  140.00               .585     107             8.84       .3515E+00
0 CBAR-P     RATE-PK      CBAR-PK    TDB  TDB-EX       TW       RW        K  DELTEF
*                                                                                      XMC 1   XMC 2   XMC 3   XMC 4   XMC 5   XMC 6   XMC 8   XMC 9
  23.85 - .3003E+00         25.11 159.63  159.33   158.53     .808        4  100.00     9.07   20.25   22.84   24.52   25.75   26.71   27.99   28.26
  24.35 - .3583E+00         26.07 158.90  158.55   157.80     .823        4  100.00     9.38   20.51   23.28   25.07   26.42   27.57   29.07   29.38
  25.19 - .4148E+00         27.20 158.04  157.83   156.50     .841        4  100.00     9.72   20.84   23.75   25.89   27.28   28.83   30.38   30.74
  25.92 - .4470E+00         28.09 157.05  156.58   155.31     .861        4  100.00    10.14   21.13   24.18   26.23   28.03   29.54   31.49   31.89
  26.27 - .4382E+00         28.38 155.98  155.48   154.15     .862        4  100.00    10.57   21.30   24.37   26.49   28.35   29.91   31.93   32.34
  26.27 - .3999E+00         28.21 154.87  154.38   153.04     .702        4  100.00    11.03   21.37   24.39   26.47   28.30   29.83   31.81   32.21
  26.11 - .3558E+00         27.83 153.77  153.28   151.94     .723        4  100.00    11.51   21.40   24.33   26.32   28.07   29.52   31.40   31.79
  25.91 - .3119E+00         27.43 152.87  152.17   150.84     .744        4  100.00    12.03   21.44   24.28   26.18   27.79   29.15   30.92   31.28
0CBAR-AP    RATE-APK     CBAR-APK  TDB-EX                                NPL               CSBAV     RATE-SBK   CSBAV-K
  25.48 - .3778E+00         27.29 152.17                                 159               24.78   - .3061E+00    26.27
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(Table E3. continued)

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0 TOBS(I)     TWBS(I)    NSO(I)       TEST(I)      QRATES(I)    TZQS(I)     AIRSP(I)       NS          ROB           EMC
  185 0000    140 0000       -1        21 1800      .1875E-02   122 4000     1200E+05       4           516           7 40
0 IRFLOW      FANTIM         TIME     TOBS    TWBS                     ROB       J                    EMC              DELT
     1        3305E+01    5217E+02  185 00  140 00                     515     155                    7 40         3270E+00
0 CBAR-P      RATE-PK      CBAR-PK     TOB  TOB-EX        TW            RW       K  DELTEF
                                                                                                 %MC 1   %MC 2   %MC 3   %MC 4   %MC 5   %MC 8   %MC 8   %MC 9
  20 42  -  2081E+00        22 04  184 54  184 18  183 14      540       5  100 00   7 83   13 21   19 82   21 85   23 10   23 92   24 82   24 98
  21 01  - 2149E+00         22 88  183 59  183 14  181 91      557       5  100 00   8 13   14 52   20 31   22 35   23 58   24 41   25 33   25 50
  21 78  -  2195E+00        23 49  182 58  182 13  180 92      571       5  100 00   8 39   16 85   21 09   22 97   24 17   24 99   25 93   28 11
  22 35  -  2301E+00        24 14  181 84  181 26  160 20      582       5  100 00   8 59   18 38   21 70   23 44   24 80   25 43   28 41   28 61
  22 54  -  2399E+00        24 40  180 80  180 44  159 46      593       5  100 00   8 79   18 78   21 87   23 58   24 74   25 58   28 59   28 80
  22 45  -  2459E+00       *24 38  180 00  159 84  158 88      808       5  100 00   9 02   18 43   21 72   23 47   24 85   25 49   26 49   28 70
  22 20  - 2522E+00         24 15  159 20  158 84  157 89      618       5  100 00   9 28   17 80   21 37   23 22   24 43   25 28   28 27   28 48
  21 88  - 2815E+00         23 89  158 42  158 08  157 18      830       5  100 00   9 49   16 42   20 92   22 89   24 15   25 02   26 00   28 19
0CBAR-AP      RATE-APK     CBAR-APK  TOB-EX                                   NPL                 CSBAV     RATE-SBK   CSBAV-K
  21 83  -  2340E+00        23 84  158 08                                     172                 21 14    -.2348E+00    22 96

0 TOBS(I)     TWBS(I)    NSD(I)       TEST(I)      QRATES(I)    TZQS(I)     AIRSP(I)       NS          ROB           EMC
  170 0000    140 0000       -1        19 1400      1875E-02    122 4000     1200E+05       5           454           8 39
0 IRFLOW      FANTIM         TIME     TOBS    TWBS                     ROB       J                    EMC              DELT
     1        1145E+02    6031E+02  170 00  140 00                     454     181                    6 39         3594E+00
0 CBAR-P      RATE-PK      CBAR-PK     TOB  TOB-EX        TW            RW       K  DELTEF
                                                                                                 %MC 1   %MC 2   %MC 3   %MC 4   %MC 5   %MC 8   %MC 8   %MC 9
  18 33  - 2574E+00         19 38  169 57  169 22  168 30      473       8  100 00   8 71   11 41   14 25   18 89   21 22   22 34   23 41   23 80
  18 88  - 2844E+00         19 94  188 78  188 38  187 39      485       8  100 00   8 89   12 02   14 97   20 01   21 77   22 79   23 84   24 02
  19 50  - 2810E+00         20 84  187 91  187 52  188 50      495       8  100 00   7 07   12 47   18 77   20 89   22 33   23 32   24 33   24 52
  20 01  - 2878E+00         21 18  187 06  188 89  185 89      508       8  100 00   7 25   12 58   18 33   21 38   22 84   23 78   24 74   24 92
  20 24  - 2829E+00         21 39  188 23  185 85  184 87      518       8  100 00   7 43   12 87   18 98   21 84   23 03   23 93   24 89   25 07
  20 24  - 2721E+00         21 34  185 40  185 03  184 08      527       6  100 00   7 81   12 78   18 92   21 80   22 99   23 88   24 84   25 02
  20 11  - 2583E+00         21 15  184 59  184 22  183 27      538       8  100 00   7 80   12 88   18 51   21 39   22 82   23 72   24 89   24 87
  19 94  - 2358E+00         20 90  183 78  163 43  182 48      549       8  100 00   7 99   13 01   17 95   21 11   22 59   23 52   24 49   24 87
0CBAR-AP      RATE-APK     CBAR-APK  TOB-EX                                   NPL                 CSBAV     RATE-SBK   CSBAV-K
  19 85  - 2872E+00         20 74  183 43                                     218                 19 13    - 2465E+00    20 14

0 TOBS(I)     TWBS(I)    NSO(I)       TEST(I)      QRATES(I)    TZQS(I)     AIRSP(I)       NS          RDB           EMC
  175 0000    140 0000       -1        18 8200      .1875E-02   122 4000     1200E+05       8           .401          5 57
0 IRFLOW      FANTIM         TIME     TOBS    TWBS                     RDB       J                    EMC              DELT
    -1        1055E+02    7157E+02  175 00  140 00                     .401    210                    5 57         4882E+00
0 CBAR-P      RATE-PK      CBAR-PK     TOB  TOB-EX        TW            RW       K  DELTEF

                                                                                                 %MC 1   %MC 2   %MC 3   %MC 4   %MC 5   %MC 6   %MC 8   %MC 9
  16 30  -  1796E+00        17 32  169 34  169 05  168 29      473       7   99 07   6 71   10 42   12 74   14 85   17 25   20 04   21 68   21 93
  16 85  -  1980E+00        17 76  170 00  169 89  168 90      468       7   99 07   8 80   10 51   12 95   15 18   18 32   20 53   22 03   22 28
  17 05  -  2189E+00        18 27  170 70  170 37  169 52      459       7   99 07   8 48   10 85   13 23   15 59   19 43   21 10   22 42   22 84
  17 38  - 2353E+00         18 89  171 44  171 09  170 20      451       7   99 07   8 38   10 74   13 48   18 24   20 06   21 47   22 72   22 93
  17 45  -  2479E+00        18 84  172 21  171 86  170 94      443       7   99 07   8 23   10 70   13 53   18 58   20 19   21 58   22 83   23 04
  17 34  -  2567E+00        18 79  172 99  172 64  171 71      435       7   99 07   8 09   10 59   13 41   18 32   20 10   21 52   22 77   22 99
  17 14  -  2835E+00        18 83  173 78  173 42  172 50      428       7   99 07   5 98   10 42   13 21   15 83   19 88   21 35   22 83   22 85
  18 90  -  2895E+00        18 42  174 57  174 21  173 29      418       7   99 07   5 83   10 23   12 97   15 41   19 44   21 13   22 46   22 88
0CBAR-AP      RATE-APK     CBAR-APK  TOB-EX                                   NPL                 CSBAV     RATE-SBK   CSBAV-K
  17 03  - 2332E+00         18 34  169 05                                     337                 18 80    - 2245E+00    17 87

0 TOBS(I)     TWBS(I)    NSO(I)       TEST(I)      QRATES(I)    TZQS(I)     AIRSP(I)       NS          RDB           EMC
  180 0000    140 0000       -1        14 3800      1875E-02    122 4000     1200E+05       7           354           4 87
0 IRFLOW      FANTIM         TIME     TDBS    TWBS                     ROB       J                    EMC              OELT
     1        9551E+01    8287E+02  180 00  140 00                     354     233                    4 87         5629E+00
0 CBAR-P      RATE-PK      CBAR-PK     TOB  TOB-EX        TW            RW       K  DELTEF
                                                                                                 %MC 1   %MC 2   %MC 3   %MC 4   %MC 5   %MC 8   %MC 8   %MC 9
  13 87  -  2159E+00        15 09  179 83  179 32  178 53      367       8   94 97   5 06    8 49   10 68   12 68   14 43   18 11   19 42   20 11
  14 21  -  2180E+00        15 43  178 94  178 83  177 83      374       8   94 97   5 18    8 87   10 89   12 93   14 74   18 54   19 99   20 48
  14 80  -  2173E+00        15 83  178 24  177 93  177 11      380       8   94 97   5 26    8 87   11 16   13 25   15 10   17 10   20 45   20 84
  14 91  -  2173E+00        16 13  177 53  177 21  176 39      387       8   94 97   5 38    9 04   11 37   13 51   15 43   17 87   20 78   21 11
  15 04  -  2134E+00        18 24  176 82  176 51  175 68      394       8   94 97   5 46    9 15   11 48   13 82   15 57   17 93   20 87   21 20
  15 02  -  2083E+00        16 18  176 12  175 81  175 01      400       8   94 97   5 58    9 19   11 49   13 80   15 52   17 80   20 82   21 18
  14 91  -  1976E+00        18 03  175 44  175 14  174 35      407       8   94 97   5 86    9 20   11 45   13 52   15 37   17 50   20 88   21 04
  14 77  -  1888E+00        15 84  174 78  174 48  173 72      413       8   94 97   5 78    9 20   11 38   13 40   15 20   17 18   20 50   20 89
0CBAR-AP      RATE-APK     CBAR-APK  TOB-EX                                   NPL                 CSBAV     RATE-SBK   CSBAV-K
  14 88  -  2091E+00        15 85  174 48                                     451                 14 32    - 2023E+00    15 48

0 TDBS(I)     TWBS(I)    NSO(I)       TEST(I)      QRATES(I)    TZQS(I)     AIRSP(I)       NS          ROB           EMC
  180 0000    140 0000       -1         5 1800      1875E-02    122 4000     1200E+05       8           354           4 87
0                                                                                                                                          J      NPL
                                                                                                                                         263      460
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