AN ABSTRACT OF THE THESIS OF

Michael Dean Sandoe for the degree of Master of Science

in Forest Products presented on August 1, 1980

Title: Gluability of Platen-Dried Douglas-fir Veneer

Abstract approved: Redacted for Privacy

Dr. J. D. Wellons

This study was undertaken to determine whether Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) veneer could be platen-dried and then sucessfully glued into two-ply parallel-laminated panels.

A range of veneer thicknesses, platen temperatures and final dry moisture contents were examined. Thicknesses included were nominal 0.1, 0.2, 0.3 and 0.4 inches; platen temperatures were 325, 375, 425 and 460°F. Drying of both sapwood and heartwood was carried out to final moisture contents of either one, five or nine percent.

Gluebond quality was evaluated using shear strength and percentage wood failure as criteria. Three aging methods were employed: none, vacuum-pressure soaking and cyclic boiling.

The effective limit on subsequent gluability of platen-dried veneers was found to be a function of both platen temperature and drying time. Thin veneers (0.1 and 0.2 inch) typical of commercial plywood operations were most gluable after drying at the lowest platen temperature examined, 325°F. However, 0.4 inch thick veneers were best dried at

a high platen temperature, 460°F, and had laminate shear strengths equivalent to thin veneer panels.

Shear strength after vacuum-pressure aging appeared to be the best method of performance evaluation of parallel-laminated platen-dried veneers. Percentage wood failure was uniformly high for all veneer thicknesses and platen temperatures. Shear strength was only moderately predictable empirically; platen temperature and temperature x drying time were the most important influences on subsequent mechanical capacity.

Drying times to five percent moisture content varied from less than one minute for 0.1 inch veneer at 460°F to approximately 20 minutes for 0.4 inch sapwood veneer dried at 325°F.

Volumetric shrinkage after platen-drying at all temperatures at 35 psi and air drying at 425°F were approximately equal. Thickness shrinkage was greater for platen-dried veneer, but tangential shrinkage was lower.

Gluability of Platen-Dried Douglas-fir Veneer

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A THESIS

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Master of Science

Completed August 1, 1980

Commencement June 1981

APPROVED:

Redacted for Privacy

Professor of Forest Products in charge of major

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Date thesis is presented August 1, 1980

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ACKNOWLEDGMENTS

I wish to express my appreciation to Dr. J. D. Wellons for his help and support in preparation of this thesis.

Special appreciation is extended to Weyerhaeuser Company for supplying materials, and to the United States Forest Products Laboratory, Madison, Wisconsin, for funding and cooperation in materials preparation.

Finally, I wish to formally acknowledge the help and support of my wife, Elaine.

Table of Contents

List of Illustrations

Gluability of Platen-Dried Douglas-fir Veneer

Chapter 1. An Orientation to the Problem of Platen-Drying

The basic feature of platen-drying is the application of hot plates directly to wood surfaces with the intent to vaporize wood moisture and effect rapid drying. Heat transfer occurs primarily by conduction, rather than by slower convective processes that are typical of conventional drying methods and which rely on air as a transfer medium.

The first patent for a platen-dryer was issued in 1875 on a single opening lumber dryer (Pfeffer 1875); others soon followed having multi-openings (Miller 1893), mechanical restraints (Ford 1928) and extensive vapor transporting ducts (Bentley 1909). Modern research dates from 1952, when work was begun on platen- or press-drying at the United States Forest Products Laboratory in an attempt to meet the need for a low-cost flooring material for homes (Heebink 1953). As the principle became more fully understood, others researched both the applicability of platen-drying to low grade and difficult-to-dry species, and the improved properties of wood dried in this manner (Heebink and Compton 1966, Schmidt 1967).

Commercial veneer drying operations using platen-dryers are currently functioning in Finland and the USA. Platen-drying of plywood veneers is technically advantageous because high surface-to-volume ratios lead to rapid drying. Prototype studies were completed in Finland in

1975 by the Metsaliitto Company; production line operations were instituted in 1976. The Weyerhaeuser Company is currently drying veneers using platen-dryers in some of its softwood plywood plants in the USA.

Work has progressed to a state in which platen-drying is being considered seriously as an alternative for the production of parallel-laminated structural components (Schaffer et al 1977). This application of platen-drying has added advantages because heat stored in thick veneers during drying might be used to accelerate subsequent adhesive cure between laminae and facilitate continuous production. But such an application raises many unanswered questions.

Information is needed to determine conditions under which Douglas-fir veneers could be dried and then successfully glued both into plywood and parallel-laminated panels. Of special interest are high temperatures because rates of drying and, hence, industrial throughput are directly proportional to drying temperature. Higher temperatures might also enable the substitution of phenolic adhesives for more expensive phenol-resorcinol adhesives used for parallel-laminated structural members. Also, the effects of platen temperatures greater than 350°F on wood fiber degradation and surface chemistry are not known. Because rapid initial heat transfer creates steep moisture gradients during platen-drying, traditional limits for convection methods may not apply regarding safe drying temperatures that avoid surface inactivation, a thermal degradation of the wood surface.

Effects of other process variables are also poorly understood. The influence of final veneer moisture content (MC) on gluability is of

interest for two reasons. Industrial operations have imperfect control on final dry MC. One might hypothesize that surface inactivation was a function of final surface MC, which could itself be a function of both veneer thickness and drying temperature. Differences in gluability between platen-dried sapwood and heartwood are unknown but suspected on chemical grounds. Information on veneer thicknesses suitable for platen-drying is needed for products using stored heat for glueline cure, because an interactive effect of veneer thickness and drying temperature on subsequent gluability might be postulated.

An evaluation method sensitive to platen-drying effects is needed to assess performance of these veneers. Neither a definitive aging method nor mechanical test criterion has been documented for platen-dried materials, so both are examined in this study.

Chapter 2. Study Objectives

The objectives of this research are:

A. determine if a statistically significant change in adhesive bond strength or durability occurs as a result of platen-drying second-growth Douglas-fir veneer at platen temperatures in the range 325-460^{o}F;

B. if significant changes in bond strength or durability are found, develop predictive regression equations for bond quality based on the experimentally manipulated independent variables platen temperature, veneer thickness and final moisture content;

C. determine an effective method for assessing bond quality of parallel-laminated panels made with platen-dried veneer.

A secondary objective of the study is to

D. compare shrinkage of air-dried and platen-dried veneers.

Chapter 3. Extent and Results of Previous Work

The platen-drying process involves an interaction of equipment and wood parameters. The following sections treat each parameter separately only to simplify the discussion; complete separation of these effects is impossible in practice.

a. Equipment

Several press and caul plate configurations have been reported. The particular contact surface configuration is of interest because only wood surfaces in contact with some part of the hot platen surface are dried by conduction. Most workers have used fine-mesh Fourdrinier screens to provide ventilation on either one or both surfaces (Anonymous 1966, Heebink 1953, Lutz et al, Mustakallio and Paaki 1977), with or without ventilated cauls. Others have shown that use of completely non-ventilated systems led to no serious problems in moisture escape (Haygreen and Turkia 1968), at least at temperatures below 375°F. This option leads to the highest heat transfer efficiency because the contact areas are significantly higher. Some ventilation generally is needed at high drying temperatures.

One of the reasons for the limited acceptance of platen-drying for commercial operations has been its inherently batch-type nature. A charge is sequentially accepted, dried and discharged to the next operation. Plywood manufacturing techniques currently depend on continuous

operations for drying, even though other operations are batch-type. The interface of a batch dryer with other equipment is therefore difficult but possible. Very large platen-dryers and dry veneer inventories are required to successfully mix with the traditional plywood manufacturing methods. Likewise, production of continuously laminated structural components is more logically constructed around a continuous dryer.

b. Parameters Affecting the Drying Process

1. Species and End-Use Factors

The effectiveness of platen drying for both hardwood and softwood sawn stock and veneers has been investigated. Numerous commercially important species have been sucessfully dried, including many which are difficult to dry by conventional methods. Because such a large number of species and thicknesses have been reported, a relevant summary is presented in Table 1. The drying method has been limited generally to stock one inch or less in thickness. Platen-drying was feasible for cut stock from low grades (Haygreen and Turkia 1968), wall paneling (Anonymous 1966, Heebink and Compton 1966), veneer flooring (Heebink 1953), softwood plywood veneers (Mustakallio and Paaki 1977) and thick veneers for parallel-laminated products (Schaffer et al 1977). Because hardwoods had much longer drying times than softwoods, veneer applications predominated when hardwoods were used, in order to keep drying times within manageable limits. Severe degrade problems in high density hardwoods also prevented drying of thick specimens (Schmidt 1967).

Table 1. Summary of Platen-Dried Materials

Species	MC	Nominal Thicknesses[1]	Source
Ash	Green	.5,1	Hittmeier et al 1968
Red Oak	Green	.5,1	Anonymous 1966
White oak	Green	.5,1	Hittmeier et al 1968
Post oak	Green	.5, 1	Ibid
Hickory	Green	.5, 1	Ibid
Sweetgum	Green	.5, 1	Ibid
Blackgum	Unknown	.5, 1	Ibid
Cypress	Unknown	.5, 1	Ibid
Rock elm	Green	.5, 1	Ibid
Aspen	Green	.5, .75, 1, 1.25	Haygreen and Turkia 1968
Paper birch	Green	.5, .75, 1	Ibid
Paper birch	Green	30 mm	Schmidt, 1967
Maple	Green	Unknown	Ibid
Pitch pine	Unknown	Unknown	Anonymous 1966
American beech	Unknown	Unknown	Ibid
Eastern hemlock	Green	.375, .75	Ziegler et al 1971
European beech	Green	30 mm	Turkia and Haygreen 1968
Yellow birch	Green	.125	Heebink and Compton 1966
Black walnut	Green	.003	Lutz et al 1974
Douglas-fir	Green	.26, .52	Schaffer et al 1977
European pine	90	3.3 mm	Mustakallio and Paaki 1977
Larch	Green	10 mm	Maeda and Takasu 1970
Red lauan	Green	1.5, 2.5, 4.5mm	Nozaki and Yoshida 1975

[1] Inches, unless otherwise stated. Nominal sizes have been converted to decimals for ease of presentation.

2. Process Variables

Turkia and Haygreen (1968) identified three well-defined stages in platen-drying. Figure 1 generalizes their findings. Stage I was called the initial heating period and ended when the core temperature had stabilized.

Stage II was called the horizontal plateau. Its duration depended on the initial MC and geometry of the specimen. A higher initial MC led to a protracted plateau period. This stage ended when the last free water in the center of the board vaporized. In the case of 3/4 inch thick aspen sapwood, this plateau began at 230°F after approximately 20 minutes at a platen temperature of 340°F. The core plateau temperature appeared correlated to the boiling temperature of water, 212°F, at which point the rate of heat consumption by evaporation was exactly in balance with the rate of heat transfer to the wood (Turkia and Haygreen 1968).

In the early stages of drying, I and II, the wood was above the fiber saturation moisture content of wood and controlled by heat transfer. Platen-drying possessed heat transfer characteristics superior to convective transfer in air systems, because conduction was the primary mode of heat transfer from heated platens to wood.

During Stage III the drying process was controlled by moisture diffusion in wood rather than by heat transfer. As a result, the wood temperature increased and approached the platen temperature as the moisture content approached zero.

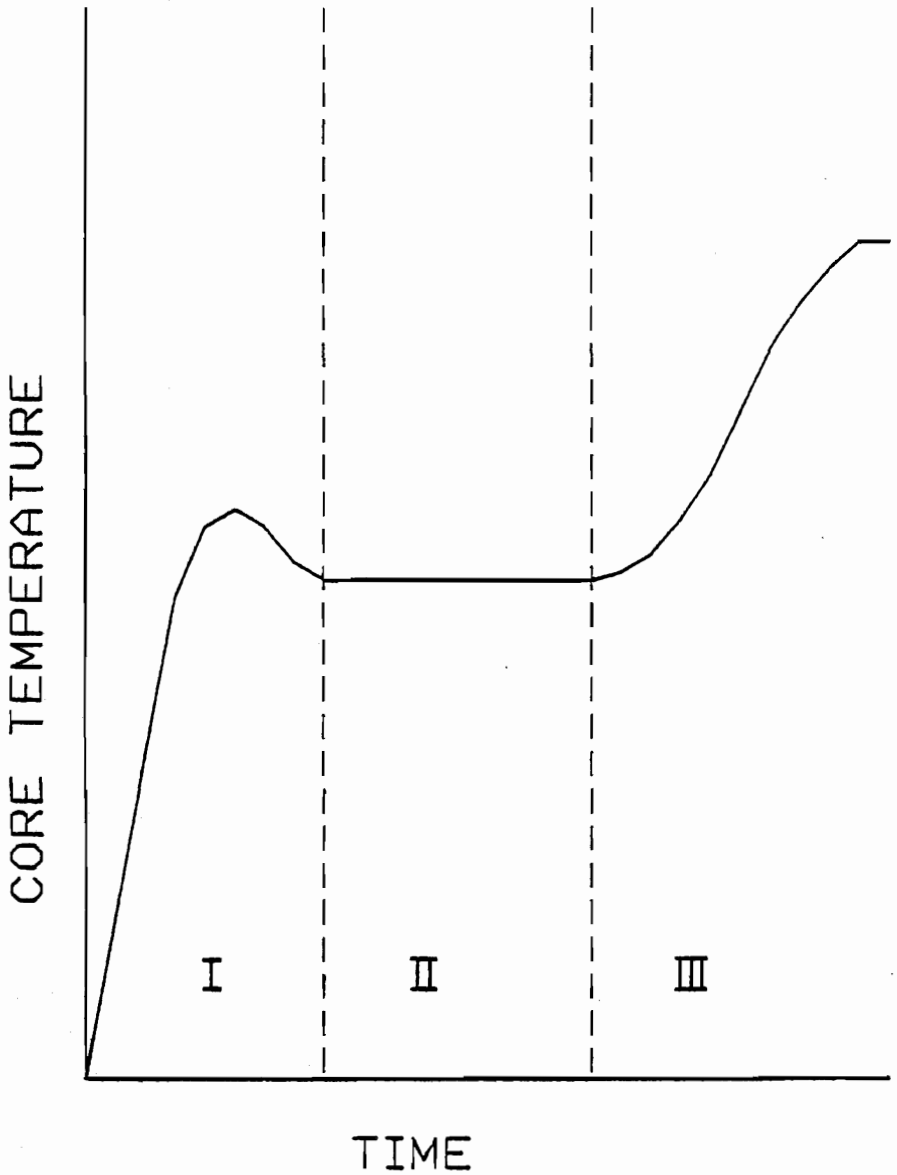


Figure 1. Stages in Platen-Drying (Turkia and Haygreen 1968)

Hittmeier et al (1968) noted a correlation between temperature differential between core and platen, and MC. These findings suggest that as the wood dries, temperature could be used as a tool to predict MC. However, the functional form for relating MC to surface temperature might be considerably different from the form applicable for core temperature. Both thickness and platen temperature could have an effect on the relationship between surface temperature and average MC. Likewise, stages in drying also might be expressed differently if surface temperature were used as the dependent variable because plateau effects would be less pronounced.

Drying curves for platen-dried materials are of the same functional form as those for conventionally dried stock, but the drying rates of the former are considerably higher. Veneer moisture content, thickness and temperature affect the specific rate. In general, drying rate is approximately a linear function of time to 40% MC for lumber and to 20-30% for very thin veneers (Koch 1964, Lutz 1974, Turkia and Haygreen 1968). Hann (1964) and Turkia and Haygreen (1968) have found that loss of water during drying was well defined by a linear function with square root of time as the independent variable. Figure 2 outlines these relationships. Ziegler (1971), using an electrically heated press, found MC changes to be best described by a linear function of the logarithm of time.

The effects of drying method and veneer thickness are illustrated by Figure 3 (Schaffer et al 1977). Platen-drying times were approximately 30 to 50% less than with jet or roller dryers. This finding

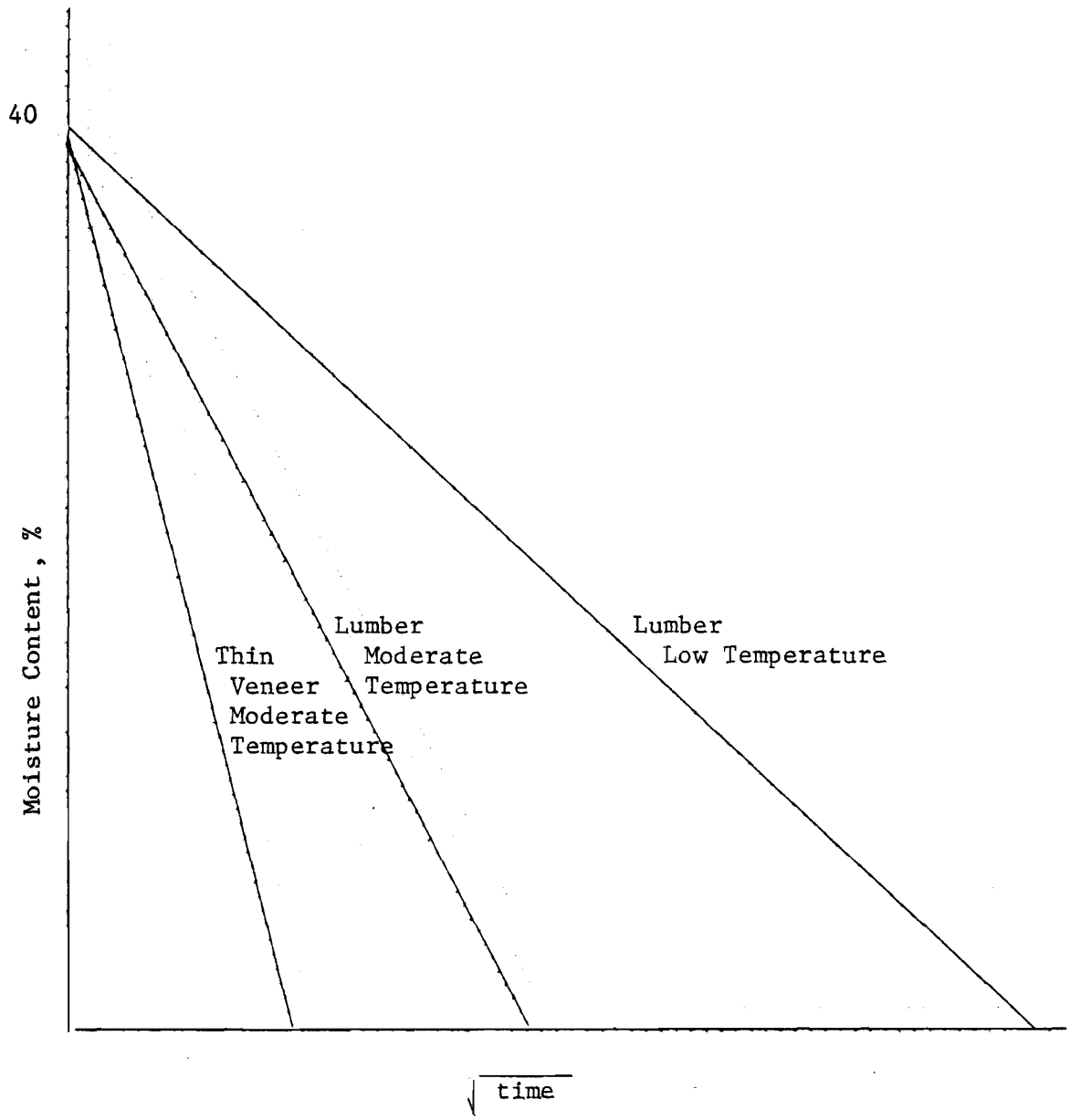


Figure 2. Platen-Drying Rate at Constant Pressure
(Hann 1964; Turkia and Haygreen 1968)

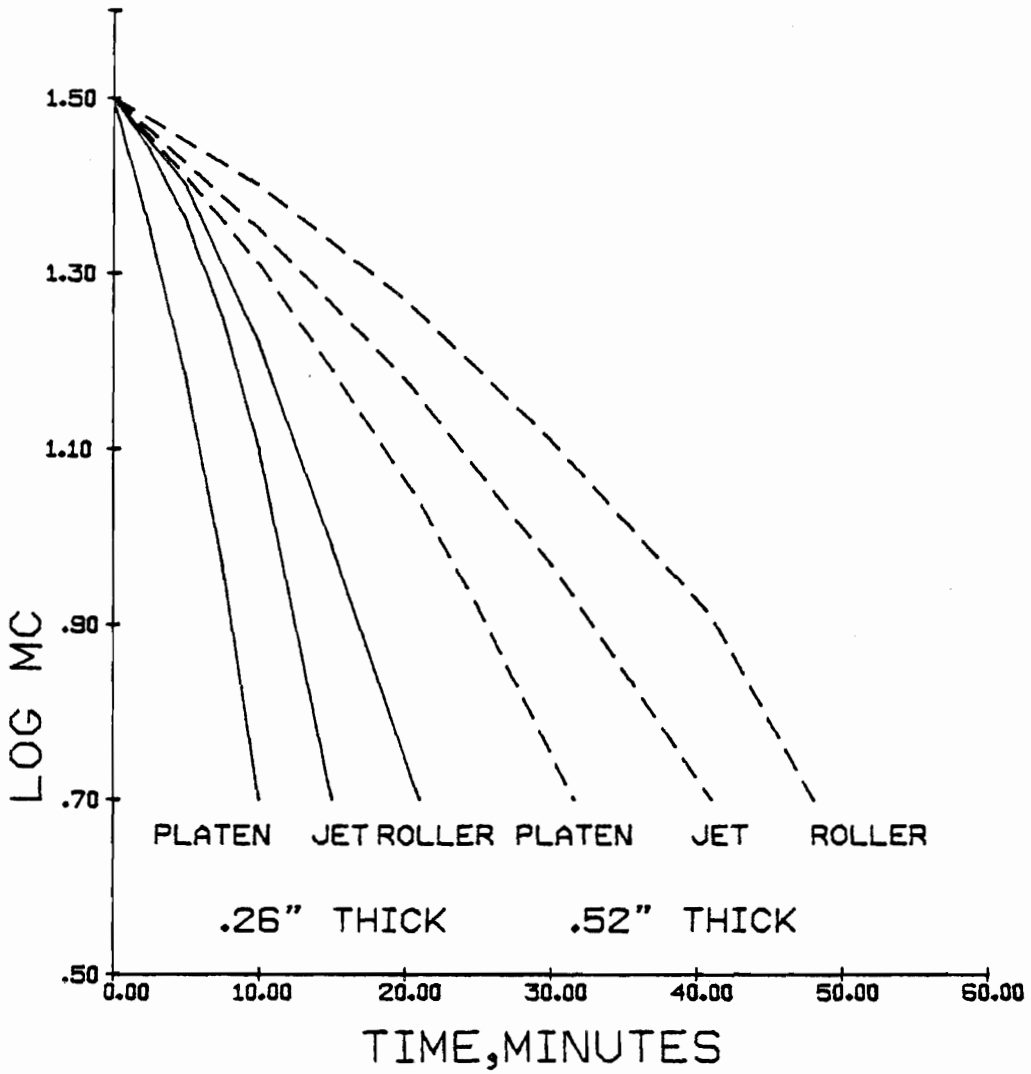


Figure 3. Relationship Between Drying Method, Veneer Thickness and Drying Rate (Schaffer et al 1977)

agrees well with findings that drying one-inch softwood veneer in superheated steam at 400°F takes 50% longer than at 355°F in a platen-dryer (Atherton and Welty 1972, Mustakallio and Paaki 1977).

It has not been resolved whether platen-drying is more desirable for thick or thin veneers. As heat is applied, it is transferred toward the center of the piece by conduction through wet cells (Turkia and Haygreen 1968). On heating, a mixture of vapor and liquid is proposed to move to the surface and escape (Hittmeier et al 1968). Therefore, Haygreen and Turkia (1968) asserted that platen-drying was more attractive for thin stock. They pointed out that as thickness increased the heat transfer surface remained constant and the surface-to-volume advantage was lost. Hittmeier et al (1968) observed drying times four to five times longer for one-inch than for one half-inch thick stock. However, Schmidt (1967) proposed that steam and air pressure expelled a significant percentage of the total water removed during drying, because air in the lumens expanded and forced water out. If Schmidt was correct it is logical to conclude that the more rapid attainment of conditions where diffusion, rather than heat transfer, controls rate of drying would favor platen-drying over convection drying, even at greater thicknesses.

Temperature has a direct, non-linear, effect on drying time. Drying times were on the order of one to two hours for one-inch thick lumber at drying temperatures of approximately 340°F. (Table 2).

Table 2. Effect of Temperature on Platen-Drying of Sawn Lumber

Temp., °F	Pressure, psi	Thickness, inches	Drying Time, minutes	Final MC, %	Remarks	Source
345	50	1/2	21-110	6	10 hard-woods	Hittmeier et al 1968
345	50	1	85-500	6	10 hard-woods	Ibid
340	50	1	85	6	Aspen at FSP	Haygreen and Turkia 1968
340	50	1	130	6	Aspen, green	Ibid
340	50	3/4	76	6	Aspen, green	Ibid
340	50	1-1/4	186	6	Aspen, green	Ibid
350	50	5/8	30-90	?	Many species, green	Anonymous 1966
350	50	5/8	55	1-3	Red oak, green	Heebink and Compton 1966
265	170	30 mm	120	1-3	European beech	Schmidt 1967

On the other hand, thin veneers were dried in only one to four minutes (Heebink 1953, Lutz 1974, Mustakallio and Paaki 1977, Schaffer et al 1977), as shown in Table 3. Maeda and Takasu (1970) found a quadratic relationship between time (t) to final moisture content and drying temperature (T) of the form $t = a-bT+cT^2$, where a, b and c were positive constants. They also observed the change in surface temperature over time. Generalized curves are shown in Figure 4. Plateaus were present but much less pronounced than those observed at the core (Turkia and Haygreen 1968).

Considerable uncertainty exists regarding effects of temperature on wood surface characteristics. Some evidence suggests that oxidation of the surface may take place at temperatures greater than 300°F (Troughton and Rozon 1974, Chow and Mukai 1972). If adhesion required the presence of sites which can bond covalently with adhesives, as Chow (1973) suggested, then loss of such sites during oxidative carboxylation would lead to surface inactivation. Hancock (1963) suggested that migration of extractives during high temperature drying might lead to the deposition of an obstructing, non-reactive coating on the wood surface and, hence, inactivation. Extractives may also serve as catalysts in oxidative reactions. Physical fiber degradation may take place as a result of pyrolysis at temperatures greater than 355°F (Chow 1971). Suchsland and Stevens (1968) demonstrated that convection drying at 500°F definitely led to reduced gluability.

Platen pressure seems to have, at most, only a minor effect on drying time. Ziegler (1971) found that with electrically heated platens,

Table 3. Platen-Drying Black Walnut Veneer (Lutz et al 1974)

Temperature, °F	Pressure, psi	Green MC,[1] %	Final MC,[1] %	Time, sec.
230	50	79	19	70
230	50	82	8	140
230	150	81	18	70
230	150	80	8	140
300	50	80	18	18
300	50	82	5	35
300	150	81	18	18
300	150	81	7	35
230[2]		80	18	140
230[2]		81	6	240

[1] Averages of three flitches

[2] Conventional roller dryer

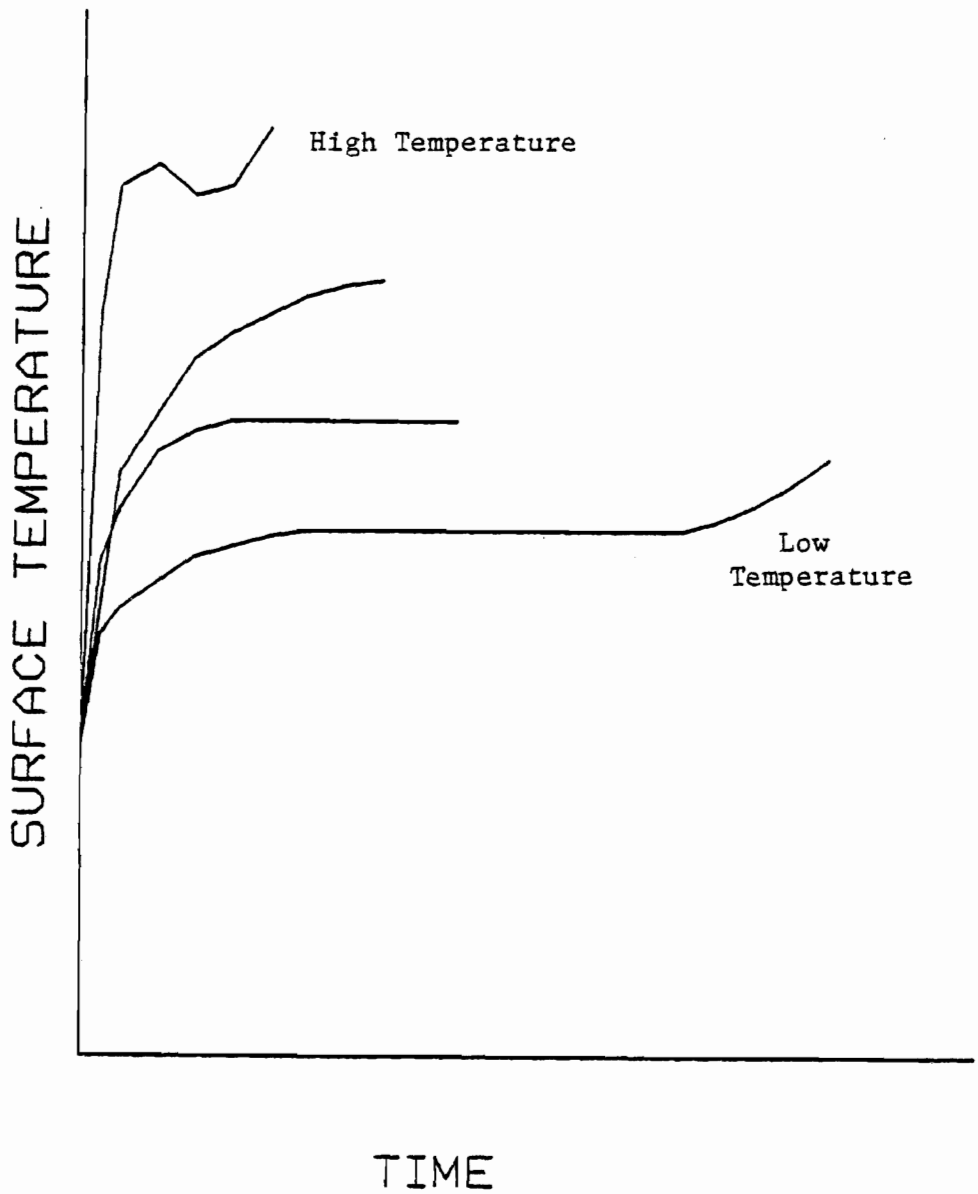


Figure 4. Variation of Surface Temperature over Time at Varying Platen Temperatures (Maeda and Takasu 1970)

increased pressure significantly reduced drying time. However, other work using steam heated platens has shown little effect of pressure (Lutz et al 1974, Schmidt 1967). Pressure in the range 50-200 psi appears to have an insignificant effect on drying times for steam heated units. Schmidt (1967) has clearly shown that pressures greater than 300 psi led to collapse and splitting of high density woods as well as hydrolysis due to higher wood temperature early in the drying cycle. Also, thickness shrinkage was greater at higher pressure.

c. Properties of Platen-Dried Material

Several physical characteristics of wood are altered by platen-drying. Chemically altered tannins lead to deeper colors (Anonymous 1966); figure is accentuated (Heebink and Compton 1966). Thickness shrinkage while drying is greater, especially at higher platen pressures (Hittmeier et al 1968) although tangential shrinkage is lower for platen-dried material (Heebink 1953, Turkia and Haygreen 1968), particularly if the final moisture content is less than nine percent. Schmidt (1967) remarked that dimensional hysteretic effects with environmental changes were reduced although some loss of this improvement occurred after extended cycling. Veneers are flatter, less twisted and less buckled than after conventional air drying (Mustakallio and Paaki 1977) with maximum effects at lower pressures and temperatures for longer drying times (Lutz et al 1974). Specific gravity appears to be nominally higher than for kiln dried stock. Hittmeier

et al (1968) reported toughness, hardness and abrasion resistance to be unchanged as a result of platen-drying. However, problems may occur at higher drying temperatures. Currier (1958) found that Douglas-fir veneer was weaker after drying in air at temperatures greater than 400°F. Troughton and Rozon (1974) showed that, irrespective of drying medium, tensile strength and work to rupture decreased with time at exposures above 360°F for initially dry micro-specimens. Saturated steam exposure was worse than hotpressing at 390°F.

Gluability and subsequent performance are also a matter of some debate. Some contend that gluability of platen-dried materials is acceptable (Jokerst 1972, Schaffer et al 1977), based on mechanical tests. However, low wood failure values but only slightly lowered ultimate loads for high density oaks were observed (Hittmeier et al 1968). The traditional correlation between percentage wood failure and shear strength is definitely in question. Several efforts have shown adequate shear strength and percentage wood failure (Hittmeier et al 1968, Jokerst 1972, Schaffer et al 1977). However, others have found lower percentage wood failure (Koch 1964) or strength (Suchsland and Stevens 1968). The latter observed an interaction between temperature and extractives, with greater effects of high temperature and high extractive content. Drying in high temperature air has been shown to lower shear strength but increase percentage wood failure or lessen the strength-wood failure correlation (Currier 1958, Kozlik 1974). Clearly, temperature, thickness and MC limits to avoid inactivated surfaces are not known currently.

d. Summary of Potentials and Problems

The platen-drying method has several advantages over other drying methods. Drying times are significantly reduced for both lumber and veneer. Platen-drying requires significantly less process energy than conventional methods. Smooth and flattened dry veneers lend themselves more easily to curtain coating and continuous lamination. Heat stored in veneers could be used to accelerate curing of adhesive bonds. Difficult-to-dry species can be more fully utilized.

A few problems are associated with the method. Thickness tolerances within a charge must be narrow as a result of rapid drying. System technology is only in the developmental stages, so commercial operations would require special design and layout services. Sophisticated and rapid materials handling equipment would be required for continuously laminated products, because highest product strength is achieved when veneers are glued immediately after drying (Schaffer et al 1977). Finally, mechanical and physico-chemical performance of platen-dried materials is still imperfectly known.

Chapter 4. Description of Experiment

a. Experimental Design

A factorial design was chosen as the most efficient method of examining effects of the different drying variables. Platen temperatures, veneer thicknesses and final veneer moisture contents were chosen at the levels shown in Table 4. Oven drying at 425^{o}F was included as a control to simulate normal convection drying. Moisture content ranges for each category were 0-2.5%, 3.5-6.5% and 7.5-11.0% for nominal 1%, 5% and 9% groups, respectively.

Six dependent variables were examined for the factorial array of the independent variables. The dependent variables included were shear strength and arcsin (percentage wood failure/100)$^{1/2}$, measured after each of three aging methods (Table 4). The arcsin transformation was used to adjust wood failure values to a more normal population distribution. Significant effects and their interactions were examined in greater detail by inclusion in regression analyses to predict glueline performance based on thickness, temperature and dry moisture content.

Table 4. Experimental Design

Independent Variables	Number of Levels	Description
Thickness	4	.1, .2, .3, and .4 inch
Drying Method	5	Platen: 325, 375, 425 and 460°F; Oven: 425°F
Final MC	3	1, 5 and 9%
Wood Type	2	Heartwood, sapwood
Replication	5	

Dependent Variables	Aging Methods
Shear Strength	None, vacuum-pressure soak, boil-dry-boil
Percentage Wood Failure	None, vacuum-pressure soak, boil-dry-boil

b. Logs and Veneer Preparation

Thirty logs of second-growth Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), 12-14 inches in diameter at the small end and 17 feet or greater in length were selected at the Weyerhaeuser plywood plant, Longview, Washington and shipped to the U.S. Forest Products Laboratory, Madison, Wisconsin. Logs were transported with bark intact and ends coated to prevent checking. On arrival in Madison, the logs were debarked and cut into four-foot peeler blocks, vat-soaked in water at 180°F for eight hours (to ensure a temperature of 140°F at a five-inch core) and randomly assigned into one of the four veneer thickness groups to be peeled into 24 by 48 inch strips. Both sapwood and heartwood were peeled from each block; veneers of mixed sap- and heartwood were discarded. Ten blocks were peeled into nominal 0.1 inch veneer, 21 into 0.2 inch veneer, 40 into 0.3 inch veneer and 42 into 0.4 inch thick veneer to produce approximately 150 veneers of each thickness. Sapwood and heartwood veneers from each block were labelled by block number, segragated and cooled to below 50°F and sprinkled with crystals of paradichlorobenzene to retard surface molding. Veneers were then wrapped in plastic, shipped to Oregon State University and stored at 35°F.

Veneers were randomly assigned to drying temperature-final moisture content treatment groups within the appropriate thickness and wood type category. Each 48 inch by 24 inch veneer was cut in half to produce two square sheets, labelled on the tight side, repackaged

in plastic and replaced in a 35°F environment. Veneer packages were produced such that all fifteen veneers in a treatment combination (three final moisture contents x five replications) remained together; matching half-sheets of veneer were labelled and stored for use in verification of drying curves or to serve as spares if test veneers failed to dry to the desired final moisture content.

c. Platen-Drying

Platen-drying was in a 24 inch by 24 inch, steam heated, single opening hot-press. The lower platen was fitted with a slotted aluminum caul plate, slotted face up. Slots were shallow grooves, spaced two inches apart and running in one direction only. The upper platen was unventilated. Temperatures during drying were monitored by thermocouples at four locations: inside the upper platen, at the upper platen-veneer interface near the veneer center, at the caul plate-veneer interface and in the lower platen. The temperature at all four locations was read once per minute using an Esterline-Angus recording potentiometer. A nominal hydraulic pressure of 35 psi was applied to each veneer sheet during the entire drying cycle. Closed press time was controlled within $\pm$ two seconds.

Accurate drying curves were needed because drying was rapid. Precise control of drying time was required to produce veneers falling within the final moisture content ranges. Twenty-five to 50 veneer

assemblies of each thickness (0.1, 0.2, 0.3 and 0.4 inch) were platen-dried at temperatures of 325, 375, 425 and 460°F for times varying from 15 seconds to 60 minutes at a nominal pressure of 35 psi. To simulate drying of thicker veneers, locally available 0.1 inch veneers were sandwiched to produce stock up to 0.4 inch thick in the green state. Each sheet or sandwich was weighed prior to drying, platen-dried and re-weighed. The samples were then ovendried to constant weight at 220°F and weighed. Initial moisture content and moisture content after drying were calculated. Samples having final moisture contents greater than 40% were assumed to have dried linearly over time. For those samples a linear regression of moisture content change (green minus platen-dried MC) versus drying time was fitted to establish the slope of the initial linear portion of the drying curve. To define the remainder of the curve, the y-intercept was arbitrarily defined as 300% MC, and the regression was used to graph moisture content down to 40% MC as a function of drying time. Veneers which had green moisture contents greater than 40% but which were less than 40% after drying were then used to fit the curvilinear lower portion of the drying curve. For example, Figure 5 describes a sample having an initial moisture content of 100%. This corresponds to an "initial time" of 1.8 minutes, based on the linear regression. After drying for 2.8 minutes, its moisture content was nine percent. The actual drying time, plus the initial time offset, describe the final time-moisture content coordinate of 4.6 minutes and nine percent MC. Many such

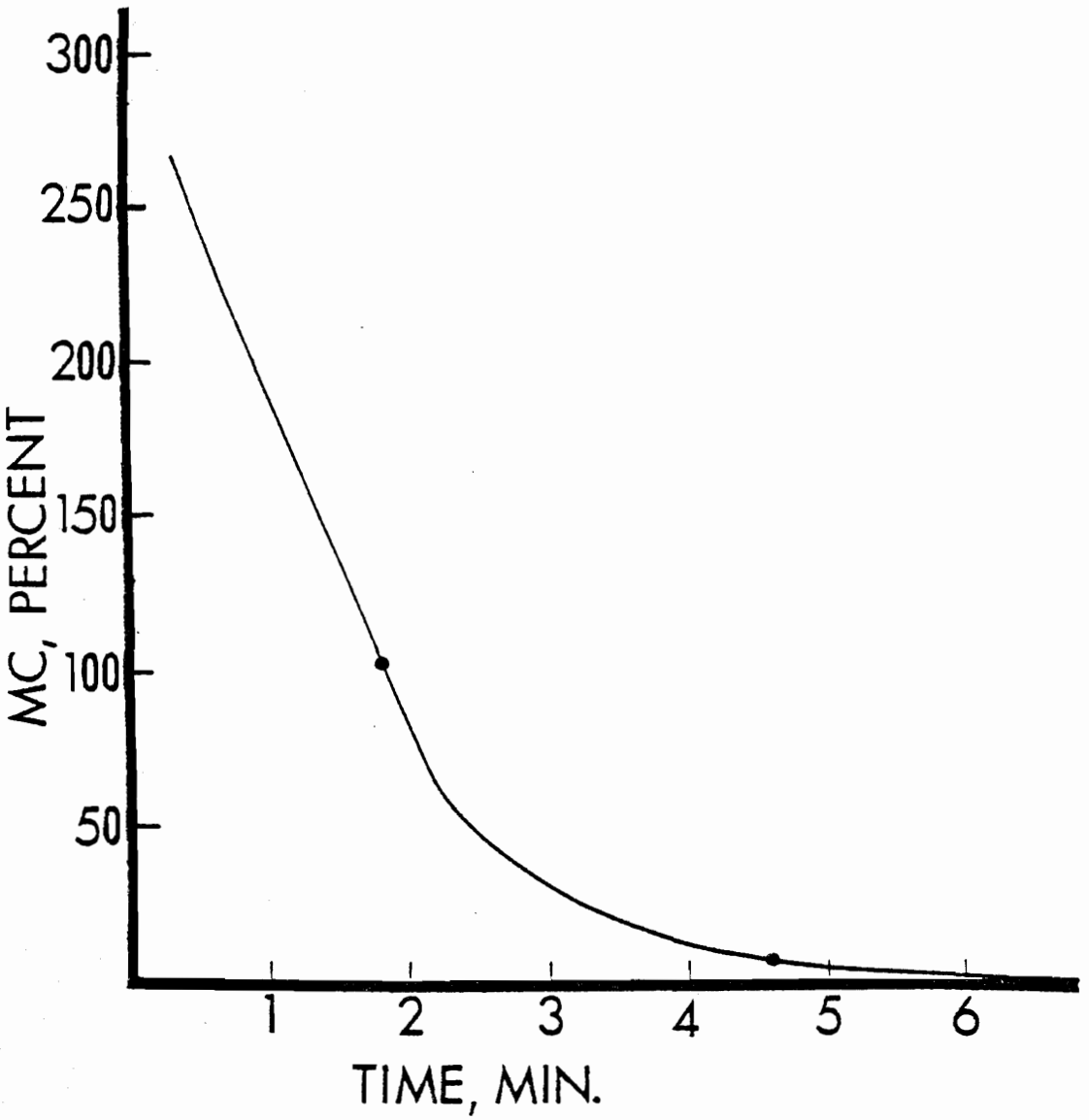


Figure 5. Development of Drying Curves

points below 40% MC were located and a quadratic function fitted to each temperature-thickness data set. Equations were found to be only marginally adequate predictors at MC levels below ten percent, based on actual drying response. Drying curves are shown in Appendix D.

These quadratic drying curves were verified and modified as necessary, using actual test veneers of all thicknesses at each temperature. No difference was observed in rate of drying between sapwood and heartwood, so these were combined into one drying curve. Drying curves were then used to normalize initial moisture content on a time basis and estimate required drying time to reach the desired final moisture content. These regression functions are purely empirical and do not bear directly on fundamental drying parameters. Similar techniques were used to establich drying curves for convection dried controls.

One day prior to drying, a strip of green veneer was removed from the actual test veneer sheets, as shown in Figure 6. Green moisture content of the strip was determined (oven drying method) and used as the veneers moisture content in calculating required drying time at the appropriate temperature. If the veneer were sapwood and the green moisture content strip had a moisture content less than 50 percent, that veneer was discarded because such a low initial moisture content would indicate either a mixed sap-heart sheet or a partly air-dried sample. At the same time the tangential dimension of the residual sheet was measured to $\pm$ 0.04 inches with a ruler and the thickness measured to $\pm$ 0.001 inches at four locations across the sheet with a dial gauge. Preliminary drying trials verified that longitudinal

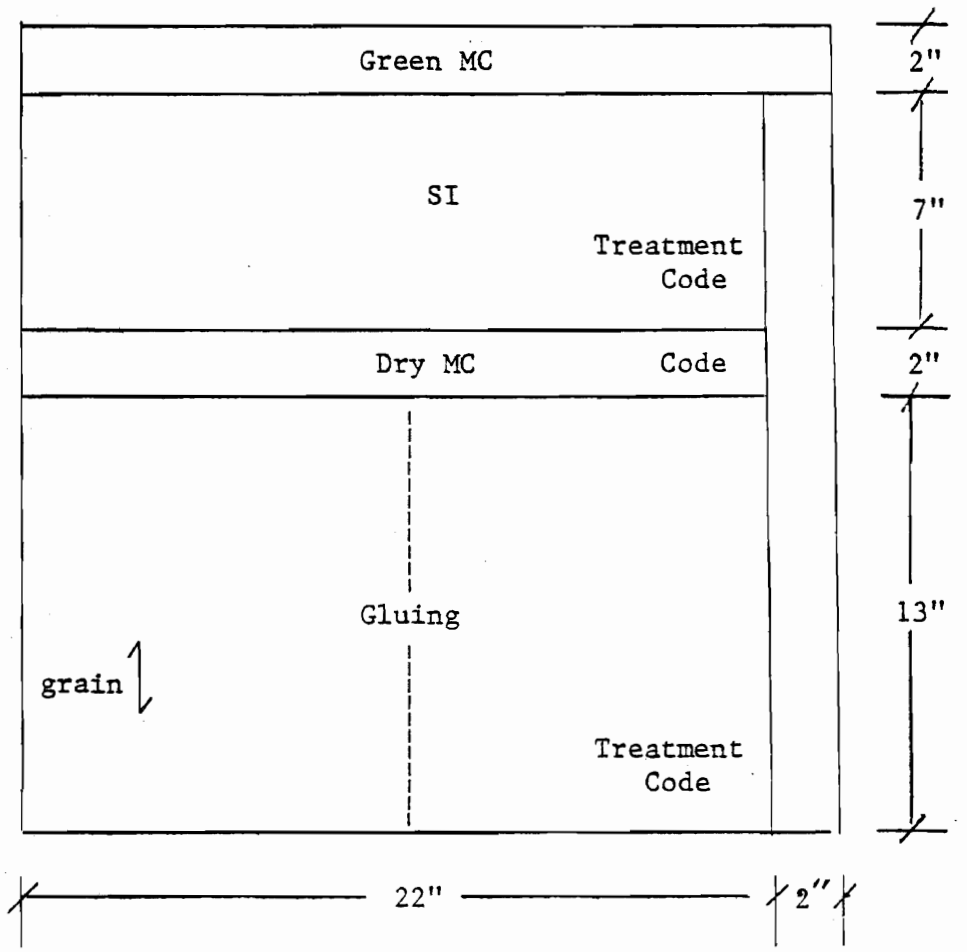


Figure 6. Veneer Cutting Plan

dimensions were unchanged by platen-drying, so this dimension was not recorded. The veneer sheet was then replaced in its plastic wrapper and stored at 35°F until drying. Veneers were removed from the cold environment approximately one hour before drying.

For the actual platen-drying veneers were placed on the slotted caul plate, lathe checks down and grain direction perpendicular to slots. The press was closed to a pressure of 35 psi for the calculated drying time. Immediately after drying, another strip of veneer (see Figure 6) was removed from the sample, weighed, placed in a small hot-press and dried to approximately constant weight. If the moisture content of the dry strip were within the desired range, the strip was placed in an oven at 220°F overnight and re-weighed to confirm that the sheet did reach the desired final moisture content. For veneer samples apparently within the dry moisture content tolerance, the sample was cut into two pieces, one for gluing and one for a companion study on surface inactivation (SI). If the moisture content after oven-drying of the dry strip was not within tolerance the entire veneer was discarded. Gluing sheets within tolerance were stickered in a 90°F, 30% relative humidity environment and left to equilibrate for at least 50 days before gluing. These conditions correspond to a nominal six percent equilibrium moisture content for solid wood.

Air-drying occurred in a forced-air oven at 425°F. Procedures for moisture content, dimensional measurements, sample cutting and conditioning were as for platen-dried veneers. The only deviation from platen-drying procedure was the occasional re-drying of a sapwood specimen for a maximum of two extra minutes after tentatively determin-

ing its moisture content to be out of tolerance. For this reason all full sheets were placed between two cool steel caul plates immediately after removal from the oven. The strip removed for dry moisture content determination was only one inch wide; if the sheet were re-dried an additional one inch strip was removed to measure dry MC, leaving gluing and SI strips of the same dimensions as for platen-dried samples. A maximum of one re-dry on any individual piece was allowed. These pieces represented approximately ten percent of the sapwood pieces dried in the oven. More predictable heartwood drying precluded the need for re-drying of heartwood.

d. Gluing and Shear Specimen Preparation

After conditioning, the 13" by 22" gluing samples were cut in half along the grain (see dotted line in Figure 6) to yield two 13" by 11" specimens. The two pieces of each gluing sample were hot-press bonded into a 13" by 11" parallel-laminated panel, lathe checks inward. Monsanto phenolic resin adhesive PF 3098 was roller coated onto one lathe-checked face at a rate dependent on veneer thickness, to account for the relatively more severe checking of the thicker veneers. Spread rates per 1000 square feet of single glueline were 33, 37, 42 and 48 pounds for 0.1, 0.2, 0.3 and 0.4 inch thick veneers, respectively. Appendix A describes the glue mixing method. As recommended by Monsanto, closed assembly time was 20 minutes, while pressing conditions were 175 psi and 300°F. Closed press times were four,

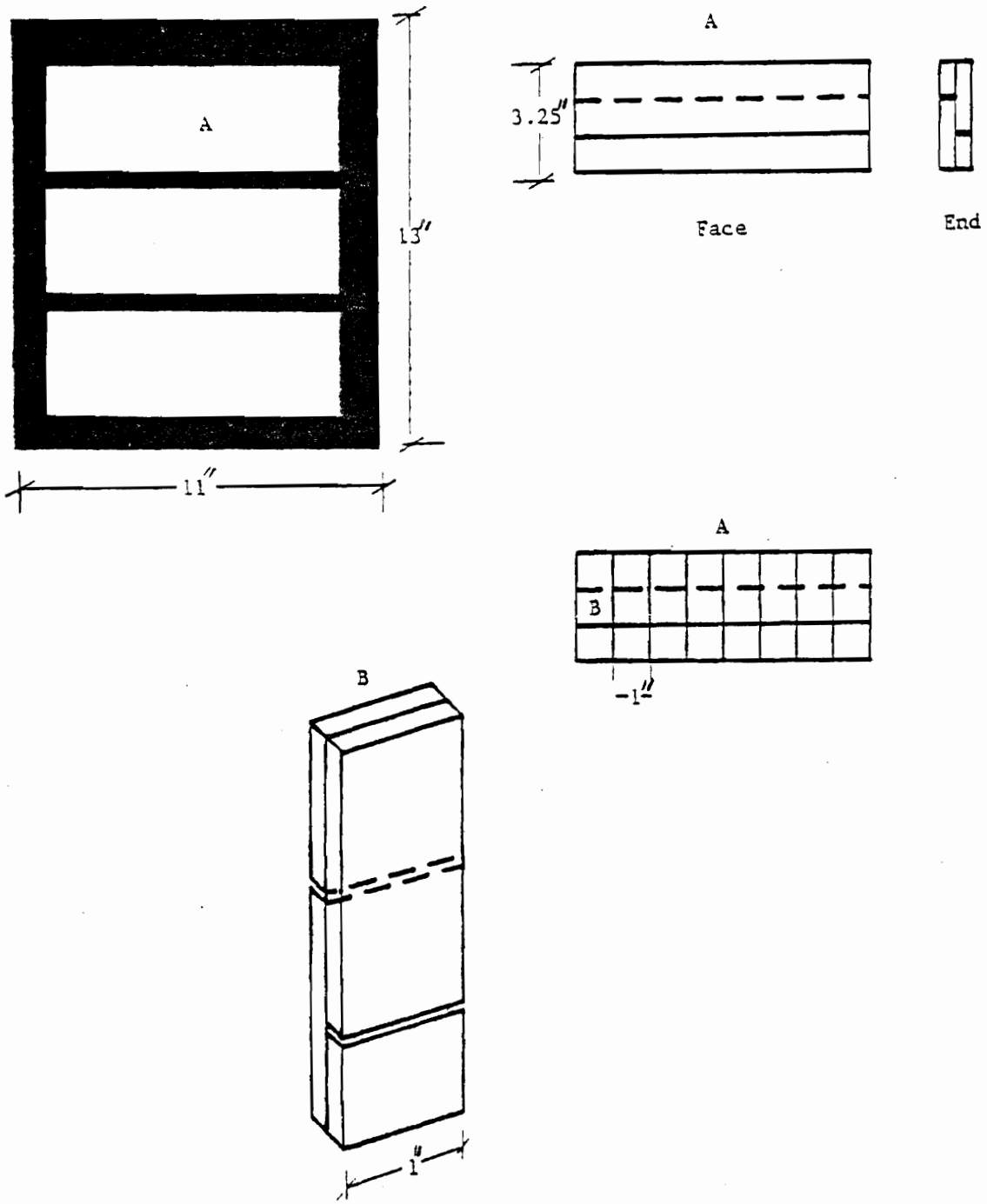
five, six and eight minutes for 0.2, 0.4, 0.6 and 0.8 inch thick panels. These times were approximately one minute longer than recommended to ensure complete cure. Cured panels were hot stacked for at least 12 hours before cutting into shear samples.

Eighteen to 24 defect free shear specimens were obtained from each panel. Cutting was as shown in Figure 7. Random samplings of three sets of six shear specimens were selected from each panel; extra specimens were set aside. Each of the three groups was wired together, along with a metal label indicating drying treatment (thickness, drying temperature, etc.) and a letter designation for the aging method.

e. Artificial Aging and Testing

A special cyclic boil-chill-dry exposure developed by Kreibich and Freeman (1968) and modified by Wilkie (1977) was used to age one-third of the samples. The treatment included two types of cycles. Type A cycles consisted of ten minutes in boiling water, five minutes of air cooling at room temperature to create thermal stresses and, finally, one hour in an oven at 220°F. Type B cycles had identical boiling and cooling segments, but drying was done at 145°F for 15 hours or overnight. A complete boil aging consisted of seven Type A cycles, one Type B cycle, seven Type A cycles and, lastly, one Type B cycle. Wilkie (1977) showed this type of cycling to be equivalent to the ASTM D3434 automatic boil test. Boiled specimens were vacuum-pressure soaked according to PS1-74 (Anonymous 1974) and sheared in

Figure 7. Shear Specimen Preparation



the wet condition at a loading rate of 600-1000 pounds per minute.

Other specimens were either subjected to a vacuum-pressure soak as per PS1-74 (Anonymous 1974) and sheared while wet in a Globe shear tester or broken dry without aging at 600-1000 pounds per minute.

Failure loads were recorded and percentage wood failure determined using the American Plywood Association procedure (Anonymous 1970). Wood failure readings were made independently by two readers. Maximum discrepancy between readings on any individual specimen was 15%. The two values were averaged and the mean value recorded as the wood failure for the specimen. Average shear strength (six specimens) and wood failure (two readings of six specimens) were treated as single observations on a panel for statistical purposes.

Chapter 5. Results

a. Drying Patterns

Platen-drying was much more rapid than convection drying at 425°F, regardless of platen temperature (see Table 5). This drying time advantage held for both sap- and heartwood, for all veneer thicknesses.

A large range of drying times was needed to reach the desired final MC ranges. Thicker veneers dried at lower platen temperatures required drying times an order of magnitude greater than thinner veneers dried at higher platen temperatures. Clearly, thickness had a much larger effect on drying time than did temperature, although both were important. Differences between sapwood and heartwood drying times were also large as a result of the significantly lower green moisture content of heartwood.

The final moisture content to which the veneer was dried was a much less important determinant of platen-drying time than sap-heart effects, veneer thickness or temperature, as seen in Table 6. As a result, it was difficult to achieve specified final moisture contents within the predetermined tolerances.

b. Bond Quality

The effects of both drying parameters and aging methods are summarized and statistically analyzed in Tables 7-18. The analyses for wood failure were on transformed data, as previously described. Effects significant at 99% probability or greater were examined and are discussed.

Table 5. Effect of Veneer Thickness and Drying Temperature on Average Drying Time to Five Percent MC

Sapwood Drying Time, minutes

Thickness, inches	Temperature, °F				
	325	375	425	460	Oven(425)
.1	2.2	1.7	1.0	1.0	14.7
.2	6.5	4.7	3.1	3.2	23.8
.3	12.8	8.6	6.5	6.0	50.8
.4	20.4	14.4	11.3	9.5	--

Heartwood Drying Time minutes

Thickness, inches	Temperature, °F				
	325	375	425	460	Oven(425)
.1	1.3	0.9	0.6	0.5	4.9
.2	4.0	2.7	1.7	1.5	12.7
.3	7.7	4.8	3.3	3.0	18.3
.4	12.8	8.2	6.7	5.5	24.7

Table 6. Relationship Between Average Platen-Drying Time, Temperature and Final Dry Moisture Content [1/]

Moisture Content, %	Temperature, °F	Drying Time, minutes	
		Sapwood	Heartwood
1	325	4.5	2.4
	375	1.8	1.6
	425	1.4	1.2
	460	1.3	0.8
5	325	2.2	1.3
	375	1.7	0.9
	425	1.0	0.6
	460	1.0	0.5
9	325	1.8	0.7
	375	1.3	0.5
	425	1.0	0.4
	460	0.8	0.3

[1/] averaged for all thicknesses

1. Relationship Between Shear Strength and Wood Failure

Values of wood failure were very high for all of the dry sheared specimens. For example, the lowest mean in any cell of Table 7 was 89%. Thickness means, while statistically different (Table 8), were uniformly high. Although the thickness x method and thickness x wood interactions were highly significant, values of differences between these cell means are not meaningful from a practical point of view.

Wood failure after vacuum-pressure treatment (Table 9) was also quite high at all levels of the experimental variables. The analysis of variance (Table 10) suggests that percentage wood failure after VP aging was affected by veneer thickness and wood type, as well as by the interactions of thickness and method, thickness and wood type, method and wood type and thickness, method and final moisture content. Table 9 clearly shows the practical lack of importance of these effects on wood failure. Detailed interpretation of these patterns was not warranted because the American Plywood Association criterion for acceptable bond quality is 85% wood failure or greater.

Except for four veneer thickness-temperature combinations, the percentage wood failure after vacuum-pressure aging was adequate under the 85% criterion. Only 0.3 and 0.4 inch veneers dried at 325°F to five percent MC, 0.3 inch veneer convection dried in air at 425°F

Table 7. Wood Failure of Dry Specimens

Percentage Wood Failure, Sapwood

Thickness, inches	Temperature, °F					
	325	375	425	460	Oven(425)	Mean
.1	97	97	94	98	98	97
.2	94	92	89	96	97	94
.3	98	99	98	97	94	97
.4	97	97	96	95	--	96
Mean	96	96	94	96	96	96

Percentage Wood Failure, Heartwood

Thickness, inches	Temperature, °F					
	325	375	425	460	Oven(425)	Mean
.1	98	99	100	99	98	100
.2	96	95	95	98	99	97
.3	96	97	99	96	92	96
.4	94	94	95	96	99	96
Mean	96	96	97	97	97	97

Table 8. Analysis of Variance of Transformed Wood Failure for Dry Specimens

Source of Variation	Sum of Squares	DF	Mean Square	F	Probability, %[2/]
Thick	.573	3	.191	21.35	0.1
Method	.021	4	.005	.59	67
MC	.040	2	.020	2.26	10.5
Wood	.059	1	.059	6.62	1.0
Thick x Method	1.445	12	.120	13.46	0.1
Thick x MC	.023	6	.004	.42	86
Thick x Wood	.370	3	.123	13.77	0.1
Method x MC	.205	8	.026	2.87	0.4
Method x Wood	.178	4	.044	4.97	0.1
MC x Wood	.007	2	.004	.39	68
Thick x Method x MC	.507	24	.021	2.36	0.1
Thick x Method x Wood	.148	11	0.13	1.51	12
Thick x MC x Wood	.195	6	.033	3.64	0.2
Method x MC x Wood	.133	8	.017	1.86	6.5
Residual[1/]	4.329	484	.009		
Total	8.088	578			

[1/] including four-way interactions

[2/] probability that difference occurred by chance rather than as a result of treatment

Table 9. Wood Failure of VP Specimens

Percentage Wood Failure, Sapwood

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	89	91	78	93	93	89
.2	90	93	90	90	92	91
.3	85	88	82	87	84	85
.4	88	86	90	88	--	88
Mean	88	90	85	90	90	89

Percentage Wood Failure, Heartwood

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	97	96	98	99	97	97
.2	96	96	97	98	94	96
.3	88	87	92	90	93	88
.4	83	84	89	90	93	88
Mean	91	91	94	94	92	92

Table 10. Analysis of Variance of Transformed Wood Failure for Vacuum-Pressure Soaked Specimens

Source of Variation	Sum of Squares	DF	Mean Square	F	Probability, % [2/]
Thick	2.485	3	.828	74.13	0.1
Method	.168	4	.042	3.76	0.5
MC	.005	2	.002	.21	81
Wood	1.087	1	1.087	97.25	0.1
Thick x Method	.541	12	.045	4.04	0.1
Thick x MC	.080	6	.013	1.20	31
Thick x Wood	.896	3	.299	26.74	0.1
Method x MC	.135	8	.017	1.51	15
Method x Wood	.381	4	.095	8.53	0.1
MC x Wood	.015	2	.007	.66	52
Thick x Method x MC	.725	24	.030	2.70	0.1
Thick x Method x Wood	.229	11	.021	1.86	4.2
Thick x MC x Wood	.104	6	.017	1.56	16
Method x MC x Wood	.070	8	.009	.79	61
Residual [1/]	5.409	484	.011		
Total	11.988	578			

[1] including 4-way interactions

[2] probability that difference occurred by chance rather than as a result of treatment

to nine percent MC and 0.4 inch veneer platen-dried at 375°F to nine percent moisture content failed the criterion. There is certainly no general evidence that thicker veneers and higher temperatures led to unacceptably low wood failure, although lower wood failures were obtained consistently when thick veneers were dried at lower temperatures for longer times.

Percentage wood failure after cyclic boil aging was extremely high for all treatment combinations (Table 11). Although Table 12 describes the significant main effects and interactions, the high values of all class means preclude any meaningful discussion of differences; all combinations exhibited highly satisfactory performance. Worthy of note, however, is that the percentage wood failure after boiling was higher than after vacuum-pressure soak treatment.

Shear strength exhibited much more total variation than did wood failure after all three aging methods. Strength was highest for dry specimens; strength after boiling was somewhat lower than after VP soak.

A cross-classification of mean dry shear strengths and the matching analysis of variance are shown in Tables 13 and 14. In general, no significant loss in shear strength occurred as temperature increased. The only significant main effect was veneer thickness. The lower strengths with 0.4 inch veneer is understandable, but the increase in strength with thickness from 0.1 to 0.3 inch veneer is inconsistent with the fact that lathe checks were relatively more severe in thicker veneers. This change could have resulted from specimen geometry effects rather than from true differences in bond quality. The thin-

Table 11. Wood Failure of Cyclic Boil Specimens

Percentage Wood Failure, Sapwood

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	97	97	93	99	99	97
.2	95	95	95	96	95	95
.3	96	97	96	97	97	97
.4	96	93	96	97	--	96
Mean	96	96	95	97	97	96

Percentage Wood Failure, Heartwood

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	100	99	100	100	98	99
.2	100	99	99	100	98	99
.3	99	97	99	98	98	98
.4	94	90	97	98	98	95
Mean	98	96	99	99	98	98

Table 12. Analysis of Variance of Transformed Wood Failure for Cyclic Boil Specimens

Source of Variation	Sum of Squares	DF	Mean Square	F	Probability, α[2/]
Thick	.727	3	.242	32.24	0.1
Method	.142	4	.035	4.71	0.1
MC	.002	2	.001	.16	85
Wood	.836	1	.836	111.18	0.1
Thick x Method	.464	12	.039	5.14	0.1
Thick x MC	.069	6	.011	1.52	17
Thick x Wood	.400	3	.133	17.75	0.1
Method x MC	.096	8	.012	1.60	12
Method x Wood	.172	4	.043	5.73	0.1
MC x Wood	.001	2	.001	.10	91
Thick x Method x MC	.402	24	.017	2.23	1.0
Thick x Method x Wood	.112	11	.010	1.36	19
Thick x MC x Wood	.022	6	.004	.49	81
Method x MC x Wood	.029	8	.004	.48	87
Residual[1/]	3.639	484	.008		
Total	6.903	578			

[1] including 4-way interactions

[2/] probability that difference occurred by chance rather than as a result of treatment

Table 13. Shear Strength of Dry Specimens

Sapwood Shear Strength, psi

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	579	551	604	457	453	529
.2	633	651	649	531	553	603
.3	637	558	580	557	712	609
.4	534	515	509	626	---	546
Mean	596	569	586	543	573	572

Heartwood Shear Strength, psi

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	460	441	445	470	476	458
.2	651	593	663	510	560	595
.3	663	684	535	639	727	650
.4	535	515	588	639	477	551
Mean	577	558	558	564	560	563

Table 14. Analysis of Variance of Shear Strength of Dry Specimens

Source of Variation	Sum of Squares	DF	Mean Square	F	Probability, %[2/]
Thick	1572399.943	3	524133.314	69.04	0.1
Method	81303.511	4	20325.878	2.68	3.1
MC	21630.867	2	10815.433	1.42	24
Wood	11657.548	1	11657.548	1.54	22
Thick x Method	1220055.830	12	101671.319	13.39	0.1
Thick x MC	49066.502	6	8177.750	1.08	38
Thick x Wood	278981.205	3	92993.735	12.25	0.1
Method x MC	29789.403	8	3723.675	.49	86
Method x Wood	62807.629	4	15701.907	2.07	8.4
MC x Wood	5842.385	2	2921.193	.38	68
Thick x Method x MC	227345.455	24	9472.727	1.25	19
Thick x Method x Wood	326790.620	11	29708.238	3.91	0.1
Thick x MC x Wood	78357.025	6	13059.504	1.72	11
Method x MC x Wood	44064.402	8	5508.050	.73	67
Residual[1/]	3681811.115	485	7591.363		
Total	765557.716	579			

[1/] including four-way interactions

[2/] probability that difference occurred by chance rather than as a result of treatment

nest veneers tended to bend as well as shear, leading to potential stress concentrations.

A similar cross-classification for specimens aged by VP treatment (Tables 15 and 16) revealed again that strength was significantly lower for the thickest veneers. However, 0.4 inch veneers laminated into parallel-laminated panels were stronger the higher the drying temperature. Similar patterns of strength loss with thickness and drying temperature were observed after boil aging (Table 17). The statistical summaries in Tables 16 and 18 verify that these effects were real.

Vacuum-pressure and cyclic boil aging were expected to accentuate the effects of experimental variables on bond quality. Consistent patterns between these two degradation methods suggest that they did detect experimental effects. The patterns of decrease after VP and boil aging strongly imply a drying time-platen temperature effect on bond strength. However, dry shear strength was insensitive to such effects suggesting that serious thermal damage to the wood structure that would lower mechanical properties did not occur at any temperature or for any veneer thickness. No pattern of variation in dry shear strength appears totally consistent with accountable behavior.

Wood failure of parallel-laminated products has previously been shown to be a poor indicator of bond quality (Schaffer et al 1977). Presumably, stresses in the glue film which result from dimensional changes during accelerated aging are much lower for parallel-laminates

Table 15. Shear Strength of VP Specimens

Sapwood Shear Strength, psi

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	459	422	483	395	405	433
.2	445	436	456	371	395	421
.3	393	361	384	386	413	387
.4	319	330	327	403	---	345
Mean	404	387	412	389	404	397

Heartwood Shear Strength, psi

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	445	451	428	403	443	434
.2	511	479	483	429	438	468
.3	473	450	407	433	491	451
.4	339	349	371	387	333	356
Mean	442	432	422	413	426	427

Table 16. Analysis of Variance of Shear Strength of Vacuum-Pressure Soaked Specimens

Source of Variation	Sum of Squares	DF	Mean Square	F	Probability, %[2]
Thick	758597.072	3	252865.691	81.97	0.1
Method	42459.568	4	10614.892	3.44	0.9
MC	7735.994	2	3867.997	1.25	29
Wood	142286.434	1	142286.434	46.12	0.1
Replication	4595.12	4	1148.78	.37	80
Thick x Method	319061.216	12	26588.435	8.62	0.1
Thick x MC	28838.565	6	4806.427	1.56	16
Thick x Wood	89114.008	3	29704.669	9.63	0.1
Method x MC	35477.488	8	4434.686	1.44	18
Method x Wood	28207.241	4	7051.810	2.29	5.9
MC x Wood	4827.045	2	2413.523	.78	46
Thick x Method x MC	104048.004	24	4335.333	1.40	9.7
Thick x Method x Wood	52239.511	11	4749.046	1.54	11
Thick x MC x Wood	26182.284	6	4363.714	1.42	21
Method x MC x Wood	27169.207	8	3396.151	1.10	36
Residual[1]	1488512.028	484	3084.932		
Total	3127927.807	578			

[1] including four-way interactions

[2] probability that difference occurred by chance rather than as a result of treatment

Table 17. Shear Strength of Cyclic Boil Specimens

Sapwood Shear Strength, psi

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	456	400	463	381	370	414
.2	412	408	421	349	359	390
.3	374	339	359	341	405	364
.4	321	288	281	370	---	315
Mean	391	359	381	360	378	371

Heartwood Shear Strength, psi

Thickness, inches	Temperature, °F					Mean
	325	375	425	460	Oven(425)	
.1	411	420	412	379	433	411
.2	473	434	453	407	423	438
.3	431	416	373	411	487	424
.4	321	300	330	351	308	322
Mean	409	392	392	387	413	399

Table 18. Analysis of Variance of Shear Strength of Cyclic Boil Specimens

Source of Variation	Sum of Squares	DF	Mean Square	F	Probability, %[2/]
Thick	846103.638	3	282034.546	91.38	0.1
Method	53416.081	4	13354.020	4.33	0.1
MC	35210.452	2	17605.226	5.70	0.2
Wood	120543.821	1	120543.821	39.06	0.1
Replication	2396.9	4	599.22	.19	90
Thick x Method	319205.724	12	26600.477	8.62	0.1
Thick x MC	8096.890	6	1349.482	.44	85
Thick x Wood	88426.626	3	29475.542	9.55	0.1
Method x MC	39491.616	8	4936.452	1.60	12
Method x Wood	41953.883	4	10488.471	3.40	0.9
MC x Wood	4606.630	2	2303.315	.75	48
Thick x Method x Wood	73954.608	11	6723.146	2.18	1.5
Thick x Method x MC	111932.218	24	4663.842	1.51	5.8
Thick x MC x Wood	21170.151	6	3528.359	1.14	34
Method x MC x Wood	18272.839	8	2284.105	.74	66
Residual[1/]	1491445.863	484	3086.452		
Total	3268804.145	578			

[1/] including four-way interactions

[2/] probability that difference occurred by chance rather than as a result of treatment

than for cross-laminates. Therefore, wood failure percentages generally are high for parallel-laminated specimens, making shear strength a better indicator of bond quality. The work of Bohlen (1972) appears to confirm that shear strength is a better quality indicator for platen-heated samples.

In contrast, Chow and Chunsi (1979) suggest that wood failure is a better estimator of bond quality, at least for cross-laminated hardwood specimens. They have shown that shear strength is insensitive to changes in percentage wood failure at levels of the latter greater than 80%. However, in contradiction to their conclusion, high percentage wood failure may also result from mechanical or thermal surface damage which significantly lowers shear strength.

Although percentage wood failure may be a reasonable predictor of the quality of adhesion at an interface, other bulk factors also have significant effects on mechanical performance of laminates. These considerations lead to the conclusion that although bond strength might be a more reliable measure of bond quality in parallel-laminates, wood failure should not be ignored.

Wood failure results presented in Tables 7, 9 and 11 show that consistently high values were measured for all thicknesses, platen temperatures, wood types and aging methods. Shear strengths, on the other hand, did vary systematically and significantly with experimental variables and are the basis for subsequent discussion of glueline performance.

2. Selection of Aging Method Most Appropriate for Performance Evaluation

Because shear strength of dry specimens appeared insensitive to drying parameters, this criterion is questionable as a method to predict bond quality. Vacuum-pressure and cyclic boil aging methods led to mechanical behavior which was consistent with previous work (Troughton and Rozon 1974, Chow 1971, Suchsland and Stevens 1968, Bohlen 1972). These workers have shown that surface oxidation, pyrolytic fiber degradation and surface inactivation due to extractives migration lead to lower glueline strength at higher drying temperatures. These effects are known to be accentuated after one or more cycles of soaking in water and drying (Bohlen 1972). Because a marked drop of dry shear strength was not noted in this work, it is concluded that severe thermal damage did not result and that VP and cyclic boil aging methods are the more appropriate evaluation techniques. Boil cycling generally resulted in marginally higher wood failure values and lower shear strengths than VP aging. Extension of lathe checks during boil cycling could account for the minor differences.

Vacuum-pressure aging appears to be the best approach to identify experimental effects within the ranges of temperature and veneer thickness examined. Simple correlation coefficients between the three shear strengths recorded for each panel (dry, VP and boil) are shown in Table 19. Vacuum pressure and boil aging appear to be measuring some common property, while dry strength appears to be measuring some

slightly different characteristic. Patterns of strength variation were consistent between VP and boil results. As a consequence, the simpler and less time consuming VP method is the most attractive and appropriate aging method.

Table 19. Simple Correlation Coefficients for Breaking Loads

Comparison	r
Dry-VP	0.55
Dry-Boil	0.52
VP-Boil	0.84

3. Effect of Drying Parameters on Shear Strength After Vacuum-Pressure and Cyclic Boil Aging

To better analyze the effects of drying parameters on shear strength, a combined statistical analysis was attempted for pooled dry, VP and cyclic boil data. However, data base size and configuration constraints within the SPSS (Nie et al 1975) analysis package forced separate analyses of the dry, vacuum-pressure and boil shear strength data (Tables 14, 16 and 18). In addition, all four-way interactions and the replication main effect were lumped, of necessity, with all interactions involving replication. The sums of squares due to replication were then calculated separately using variance information generated using the SIPS (Rowe 1976) package on data grouped within replications. A strong commonality of important effects was observed between the VP and cyclic boil methods

Strength decreased significantly with thickness (Tables 15-18). This thickness effect is due to the lower strength of panels containing 0.4 inch veneer relative to 0.1, 0.2 and 0.3 inch veneers as a group, a difference of 71 psi after vacuum-pressure aging.

Drying method (temperature) was also significant (Tables 16,18) but is more difficult to explain because it interacted strongly with thickness. For the thinnest veneer (Tables 15, 17), strength was relatively constant for drying temperatures of 325, 375 and 425°F; strength was lower at 460°F. This pattern also appeared in 0.2 inch

veneer panels. However, temperature had little effect on shear strengths of panels composed of 0.3 inch veneer. The trend for 0.4 inch veneer panels was completely reversed from that for 0.1 inch panels; highest strength was obtained after drying at the highest platen temperature. The relative frequency histograms shown in Figure 8 clearly show that the apparent outliers within 0.4 inch veneer dried at 460°F are not simply a result of a few unnaturally strong specimens. Contrary to expectation, drying at high platen temperatures led to bond strengths equivalent to specimens convection dried in air at 425°F.

The apparent reversal of temperature dependence with the thickest veneer suggests that veneer surface characteristics may have been a function of some time-temperature relationship. This might account for the relatively constant shear strength of 0.3 inch veneer laminates over a range of temperatures as well as the observation that drying at the highest temperature led to best performance for the thickest veneers. Although this result is in direct contradiction to the work of Bohlen (1972), the incongruity may be due to differences in wood surface temperature both during drying and at the time of glue application.

Heartwood panels were significantly stronger than sapwood panels. The difference in means of 28 psi after vacuum-pressure aging is relatively small and difficult to explain other than by the fact that sapwood required much longer drying times and, therefore, longer exposures to high temperatures.

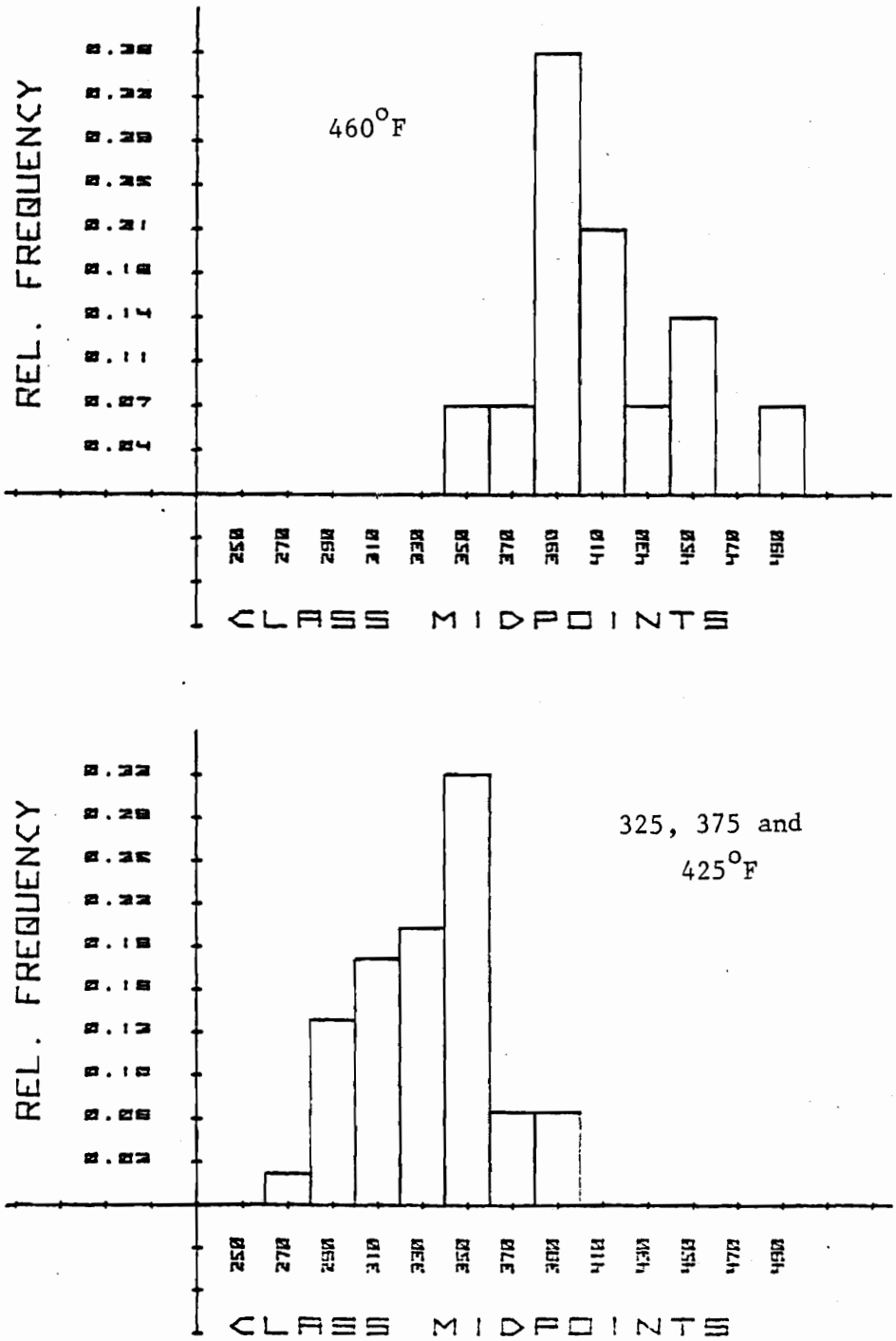


Figure 8. Frequency Distribution for VP Shear Strength of 0.8 Inch Sapwood Panels

The effect of final dry moisture content (Table 20) was significant after boil aging (Table 18) but not after vacuum-pressure aging(Table 16). This effect was systematic but small. As would be expected by considering drying time, highest shear strengths were obtained using veneers dried to the highest final moisture content, nine percent. Lowest strength was recorded after drying to one percent.

Table 20. Effect of Final MC on Cyclic Boil Shear Strength

MC, %	Mean Shear Strength, psi
1	376
5	386
9	396

A clear pattern is seen in the thickness x wood interaction (Tables 15, 17). Strength of sapwood decreased with increasing thickness, whereas strength of panels made of heartwood veneers was constant for 0.1, 0.2 and 0.3 inch veneers but decreased for 0.4 inch veneers. This pattern is consistent with the concept of a decrease in shear strength only after some time temperature threshold has been exceeded.

4. Prediction of Vacuum-Pressure Shear Strength from Drying Parameters

Main effects (thickness, temperature and final MC) and numerous combinations of these variables were initially included in stepwise regression modeling of strength of panels composed of platen-dried veneers. Models were fitted to sap- and heartwood separately; similarity of the best models led to generation of subsequent models including sap and heart strengths in a single data set. Modeling on the combined heart-sap data led to more reliable predictive equations.

Regression models were then constructed on the combined data base using all previously included variables, plus variables dealing with actual drying time and its combinations with main variables. Quadratic terms were also included. An alternative expression of platen temperature in degrees Kelvin was examined to provide a rescaling to units normally used in reaction kinetics and thermodynamics.

Models both linear and logarithmic in strength were evaluated. Equations 1 and 2 describe the best linear and logarithmic models, respectively, which satisfied the constraint that y-intercept and slope coefficients be significantly different from zero with 99% probability.

(1) $Y = 585. - 0.321T - 0.0192Tt$ $\quad R^2 = .246$

(2) $\ln Y = 6.396 - 0.000706T - 0.0000471Tt$ $\quad R^2 = .252$

where

Y = Predicted shear strength, psi

T = Platen temperature, ^{o}F

t = Drying time, minutes

Only about 25% of the total variation of the samples was accounted for by either model. This apparent lack of predictability is partly due to the fact that random error accounted for nearly 50% of the total observed variation (see Table 16). The temperature x time combination variable accounted for approximately 80% of the predictive ability of both the linear and log models.

Residuals were examined within 17 temperature-time groupings to determine if lack of fit (Draper and Smith 1966) was significant in either model. Details of this analysis are contained in Appendix B. Both the linear and logarithmic fit met criteria for acceptability.

The logarithmic model, Equation 2, is suggested as the more appropriate. Logarithmic dependence of bond strength is more fundamentally justifiable, because degradative chemical processes can generally be expressed as log functions (Gillespie and River 1975, Sasaki et al 1976, Wellons 1977). Although lack of fit considerations do not exclude the applicability of the model linear in strength, the evidence in support of the logarithmic dependence is more convincing.

Equation 2 is shown graphically in Figure 9, with heartwood isothickness lines superimposed on the surface. The response surface clearly shows the adverse effects of increasing drying time and veneer thickness on panel shear strength. The iso-chronal lines define

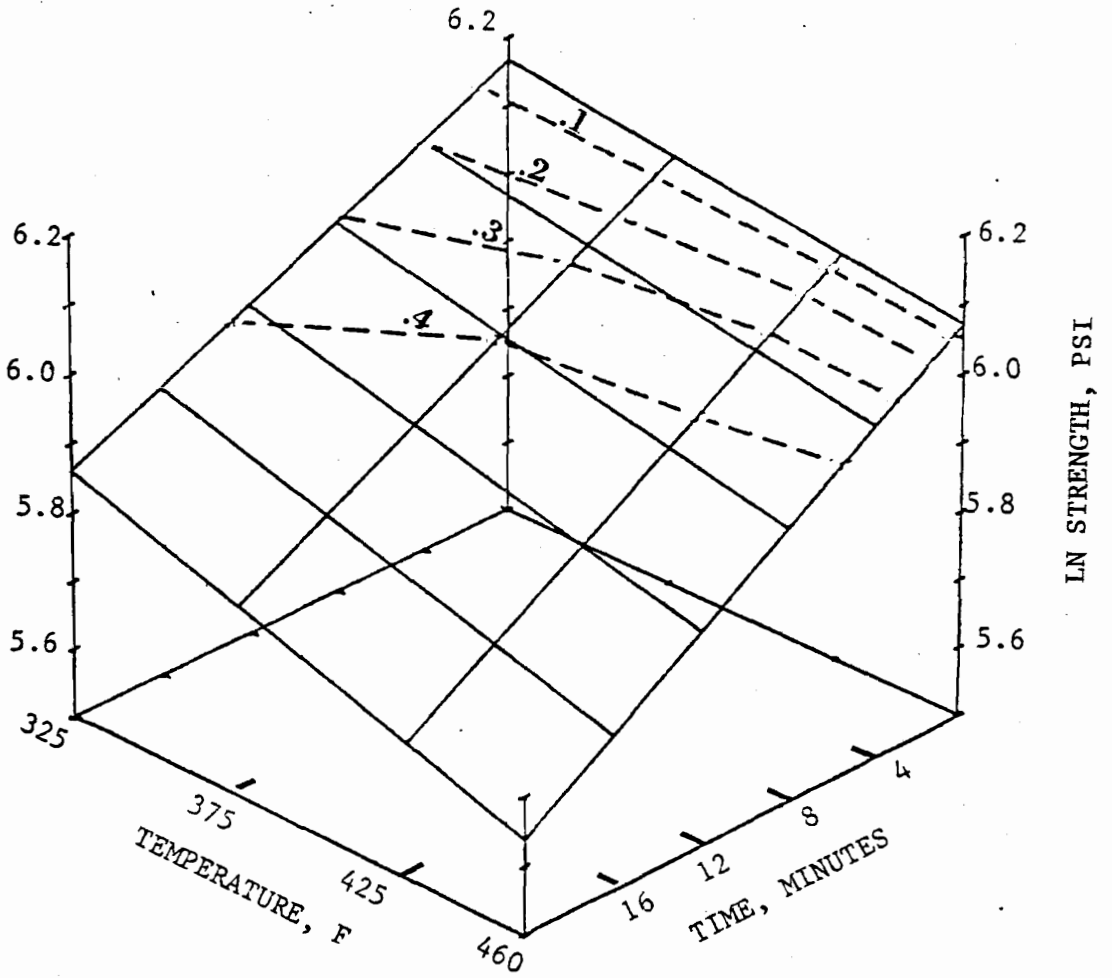


Figure 9. Relationship Between Shear Strength, Drying Temperature, Drying Time and Veneer Thickness for Heartwood

the temperature levels used in the experiment, while iso-therms were simply interpolated at equal intervals between extremes of drying times needed to accomodate both thick and thin veneers at the varying temperatures.

A similar approach for sapwood is pictured in Figure 10. Changes in thickness at a given temperature led to much larger differences in drying time and, hence, shear strength. Consistent with experimental results is the fact that drying at the highest platen temperature led to the highest shear strength, although the local extremes outlined in Table 15 are not adequately quantified in the model, for panels of 0.4 inch veneer.

Figures 9 and 10 strongly suggest that high platen temperatures are acceptable for thick heartwood veneers, but that extended drying times for sapwood at lower platen temperatures led to poor subsequent gluability. Clearly, drying time plays a more important role in relation to surface deterioration than previously understood.

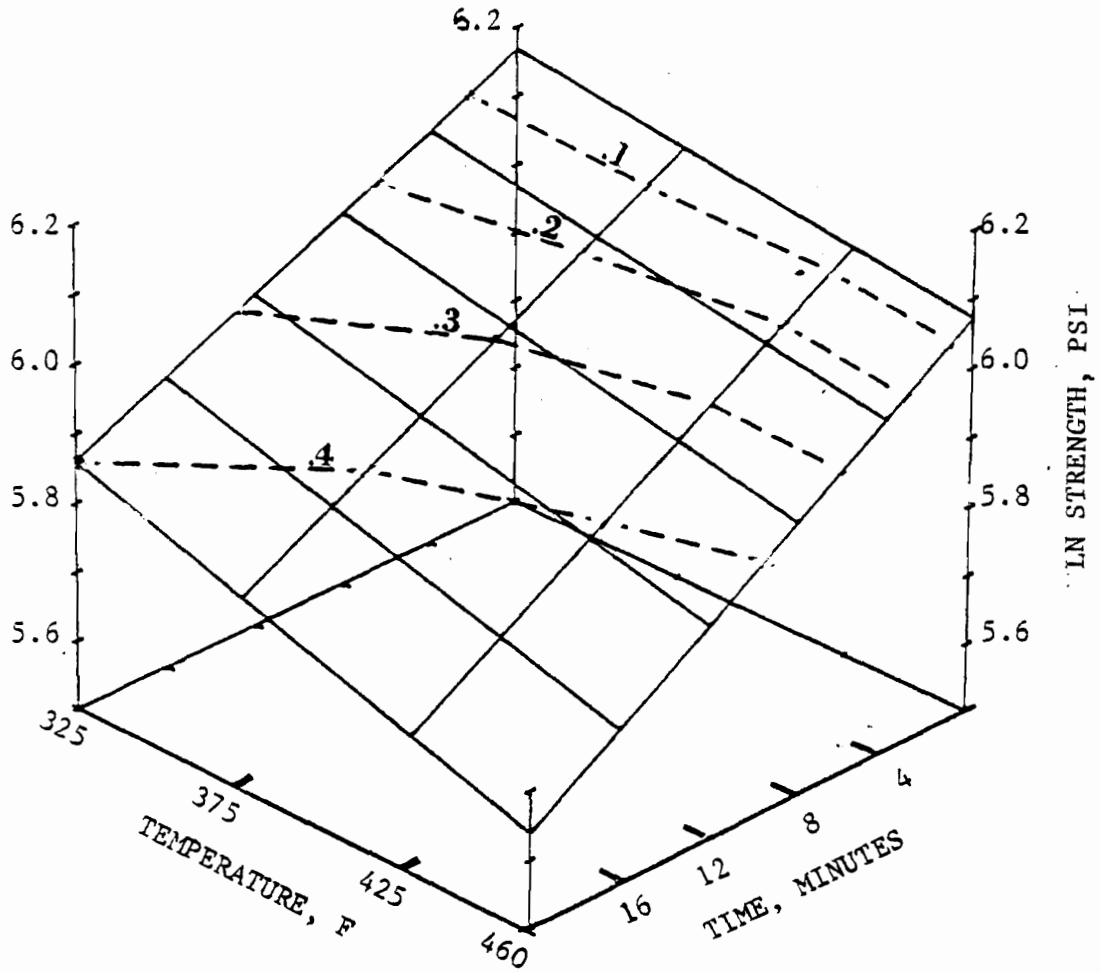


Figure 10. Relationship Between Shear Strength, Drying Temperature, Drying Time and Veneer Thickness for Sapwood

5. Solid Wood Strength of Low Temperature Air Dried Veneer

Nearly constant shear strength and high wood failure for all parallel-laminates made from platen-dried veneer might have occurred because all veneers were inactivated and weakened equally. A small experiment assessed this possibility.

Fifteen shear samples of solid wood were cut randomly from remaining 0.4 inch heartwood veneers which had been dried in air to five percent MC at 90°F. These samples were vacuum-pressure soaked, using the procedure already described, and broken in shear parallel to the grain. These 0.4 inch thick specimens were assumed to approximate two-ply specimens composed of two parallel-laminated 0.2 inch veneers.

The shear strengths of the solid wood specimens were compared to the mean shear strengths of all 0.4 inch thick parallel-laminated heartwood specimens dried to five percent MC (made from two plies of 0.2 inch veneer). These values are listed in Table 21. Specimens which were composed of two laminated veneers which had been platen-dried at 325, 375 or 425°F and solid specimens dried at 90°F were of equivalent strength. Platen-drying at 460°F did lead to a slight deterioration in strength. Interestingly, there was also a significant weakening of specimens dried in air at 425°F.

These results indicate that not all platen-dried veneers were chemically inactivated.

Table 21. Effect of Drying Temperature and Drying Mode on Shear Strength of Heartwood Specimens after Vacuum-Pressure-Soak

	Air-dried Veneer		Platen-dried Veneer			
	Solid	Laminate	Laminate			
	90°F	425°F	325°F	375°F	425°F	460°F
Mean Shear Strength, psi	489	438	511	479	482	429
Standard Deviation	77	43	60	40	48	40
n	15	15	15	15	15	15

c. Dimensional Changes

1. Radial Shrinkage

Radial shrinkage was greater after platen-drying than after convection drying. It is unknown whether this difference would be partially or completely offset by lower subsequent compression losses during glue cure under heat and pressure. Table 22 outlines the effects of veneer thickness, platen temperature and wood type on thickness shrinkage. There was no clearcut pattern of observed shrinkage as a function of platen temperature.

Analysis of variance, shown in Appendix C, suggests other main effects and interactions which influenced radial shrinkage. The following appeared to be especially important: final veneer MC, two-way interactions between thickness and method and method and wood type, and second-order interaction of thickness, method and wood type.

Interpretation of the effect of MC is straightforward: shrinkage was inversely proportional to final MC. Drying to final moisture contents of nine, five and one percent led to radial shrinkage of 8.5, 7.5 and 6.8%, respectively. These data are consistent with the findings of Maeda and Takasu (1970) that radial shrinkage of platen-dried veneers begins at 40% MC. Shrinkage appears to be due to compression effects along with the well-known moisture effect.

Table 22.
Radial Shrinkage: Interaction of Thickness, Method and Wood Type

Mean Radial Sapwood Shrinkage, %

Thickness, inches	Temperature, F					Mean
	325	375	425	460	Oven(425)	
.1	9.4	9.1	7.8	6.7	5.6	7.7
.2	8.4	4.4	8.6	9.6	4.7	7.1
.3	8.6	8.3	8.4	7.9	3.6	7.4
.4	9.2	6.8	8.6	9.6	---	8.6
Mean	8.9	7.2	8.4	8.4	4.6	7.7

Mean Radial Heartwood Shrinkage, %

Thickness, inches	Temperature, F					Mean
	325	375	425	460	Oven(425)	
.1	6.6	7.9	9.5	8.3	5.2	7.5
.2	8.6	7.4	9.2	8.4	3.7	7.5
.3	8.2	8.9	8.0	8.8	3.9	7.6
.4	8.1	8.1	7.9	7.4	4.1	7.1
Mean	7.9	8.1	8.6	8.2	4.2	7.4

2. Tangential Shrinkage

Tangential shrinkage for platen-dried veneers was much lower than shrinkage of convection dried samples, regardless of final MC or platen temperat re. Platen temperature did not affect tangential shrinkage. Tables 23 and 24 and Appendix C contain class mean data and analysis of variance information on tangential shrinkage.

The method main effect was one of several identified as significant. Thickness, MC, thickness x MC and method x MC effects were also significant. Thinner veneers shrank more tangentially than thicker veneers. The effect was most pronounced for veneers dried to nine percent final MC and least evident for veneers dried to one percent MC. Larger moisture gradients (higher center MC) may have led to partial dimensional restraint of thicker veneers.

Tangential shrinkage of convection dried veneers was inversely proportional to dry MC. However, the effect was not apparent for platen-dried veneers. Tangential shrinkage of platen-dried veneers was relatively insensitive to final moisture content.

Table 23. Tangential Shrinkage: Interaction of Method and MC

Tangential Shrinkage, %

Final MC, %	Temperature, F					Mean
	325	375	425	460	Oven(425)	
1	1.9	1.9	1.7	1.7	5.9	2.6
5	1.8	1.7	1.7	1.7	5.7	2.5
9	1.6	1.7	1.6	1.6	5.1	2.3
Mean	1.7	1.7	1.7	1.6	5.6	2.4

Table 24.

Tangential Shrinkage: Interaction of Moisture Content and Veneer Thickness

Tangential Shrinkage, %

Final MC %	Veneer Thickness, inches .1	.2	.3	.4	Mean
1	2.6	2.8	2.5	2.2	2.6
5	2.9	2.5	2.3	1.9	2.5
9	2.6	2.3	2.1	1.8	2.3
Mean	2.7	2.5	2.3	2.0	2.4

3. Volumetric Shrinkage

Calculation of volumetric shrinkage was carried out using observed values for radial and tangential shrinkage (longitudinal shrinkage was shown in preliminary studies to be immeasurably small. Shrinkage was calculated as:

$$S_V = (1 - (1 - \frac{R}{100}) (1 - \frac{T}{100}))x100$$

where

R = Radial shrinkage, percent

T = Tangential shrinkage, percent

S_V = Volumetric shrinkage, percent.

The comparison between platen temperatures showed differences in volumetric shrinkage. Table 25 outlines the average volume change as a function of temperature and wood type. Drying sapwood at 375°F led to statistically lower shrinkage (t-test) than convection drying or the other platen methods. This effect was of questionable magnitude. A similar comparison between veneer thicknesses showed no effect of thickness.

This evidence is conclusive with regard to possible minimization of volumetric losses of veneer during drying. Volumetric shrinkage appears to be equivalent for platen- and convection drying under the conditions of temperature and pressure used. Nozaki and Yoshida (1975) came to the same conclusion.

Table 25. Relationship Between Drying Temperature and Volumetric Shrinkage

Temperature, °F	Volumetric Shrinkage, %	
	Sapwood	Heartwood
325	10.5	9.5
375	8.9	9.8
425	10.0	10.1
460	10.0	9.7
425- Oven	9.9	9.6

Chapter 6. Conclusions

A. Platen-drying of second-growth Douglas-fir veneer led to statistically lower panel strength only for thicker veneers. However, the effect of temperature depended on the drying time. Panels composed of thin veneers were stronger at lower platen temperatures. Thickest veneers performed better after drying at the highest platen temperature (for a shorter time). This result is consistent with a time-temperature effect on bondability, rather than the previously accepted notion of a simple temperature effect.

B. The following equation is the best empirical model to describe the relationships between platen-drying parameters and shear strength.

$$\ln Y = 6.396 - 0.000706T - 0.0000471Tt$$

where

Y = Predicted shear strength after VP aging, psi

T = Platen temperature, ^{o}F

t = Drying time, minutes

This model accounted for only about 25% of the observed variation. Random variation and unexplained real effects were of large magnitude.

C. Shear strength after vacuum-pressure soak varied systematically and sensibly with drying parameters. Cyclic boil aging led to similar results but was more time consuming for estimating bond quality. Dry shear strengths were erratic and unrelated to experimental variables. Percentage wood failure was uniformly high and insensitive to experimental variables.

D. Platen-drying at 35 psi led to much larger thickness shrinkage but lower tangential shrinkage than air drying. Volumetric shrinkage was approximately equal for the two drying methods.

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Appendix A

Monsanto PF 3098 Phenolic Resin Adhesive for Exterior Western Softwood Plywood

Relative Amount	Component	Directions
500	Fresh water	
250	Cocob	
125	Wheat flour	1. Mix 5 minutes
150	PF 547 Resin	2. Mix 2 minutes
80	50% Caustic	3. Add gradually while mixing for 2 minutes
20	Soda ash	
1225	PF 547 Resin	4. Add soda ash; add resin in stages while mixing. Mix for 10+ minutes from start of resin addition.

Appendix B. Lack of Fit

LINEAR SHEAR STRENGTH

Source	df	SS	MS	F
Total	476	2644610	5555.9	
Regression Residual	2 474	649982 1994630	324991 4208.08	
Lack of Fit Pure error	14 460	43495 1951135	3106.93 4241.59	$0.73_{n.s.}$

LN SHEAR STRENGTH

Source	df	SS	MS	F
Total	476	15.2623		
Regression Residual	2 474	3.84782 11.4145	 .02408	
Lack of Fit Pure error	14 460	0.44538 10.96912	.0318 .0238	$1.33_{n.s.}$

$F_{05} = 1.69$

Appendix C

Analysis of Variance of Shrinkage

Analysis of Variance of Radial Shrinkage

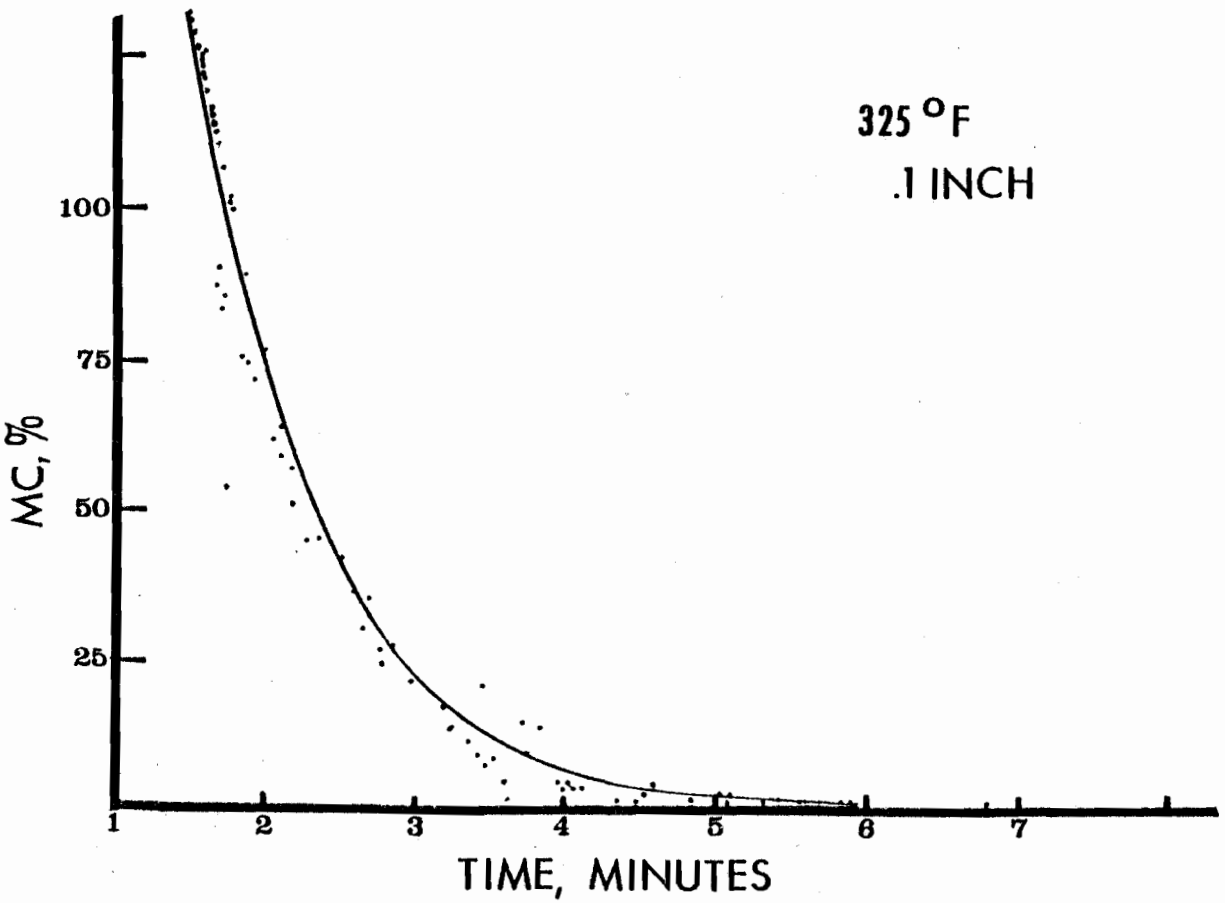
Source of Variation	Sum of Squares	DF	Mean Square	F	Probability, %[2/]
Thick	7.109	3	2.370	.72	54
Method	1292.628	4	323.157	97.62	0.1
MC	286.155	2	143.077	43.22	0.1
Wood	.706	1	.706	.21	64
Thick x Method	229.101	12	19.092	5.77	0.1
Thick x MC	28.629	6	4.771	1.44	19
Thick x Wood	25.088	3	8.363	2.53	9
Method x MC	63.597	8	7.950	2.40	1.5
Method x Wood	66.242	4	16.561	5.00	0.1
MC x Wood	1.077	2	.539	.16	89
Thick x Method x MC	155.491	24	6.479	1.96	0.4
Thick x Method x Wood	181.684	11	16.517	4.99	0.1
Thick x MC x Wood	36.628	6	6.105	1.84	8
Method x MC x Wood	39.282	8	4.910	1.48	16
Residual[1/]	1605.425	485	3.310		
Total	4031.660	579			

[1/] including four-way interactions

[2/] probability that difference occurred by chance rather than as a result of treatment

Appendix D

Drying Curves


325 °F
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MC, %
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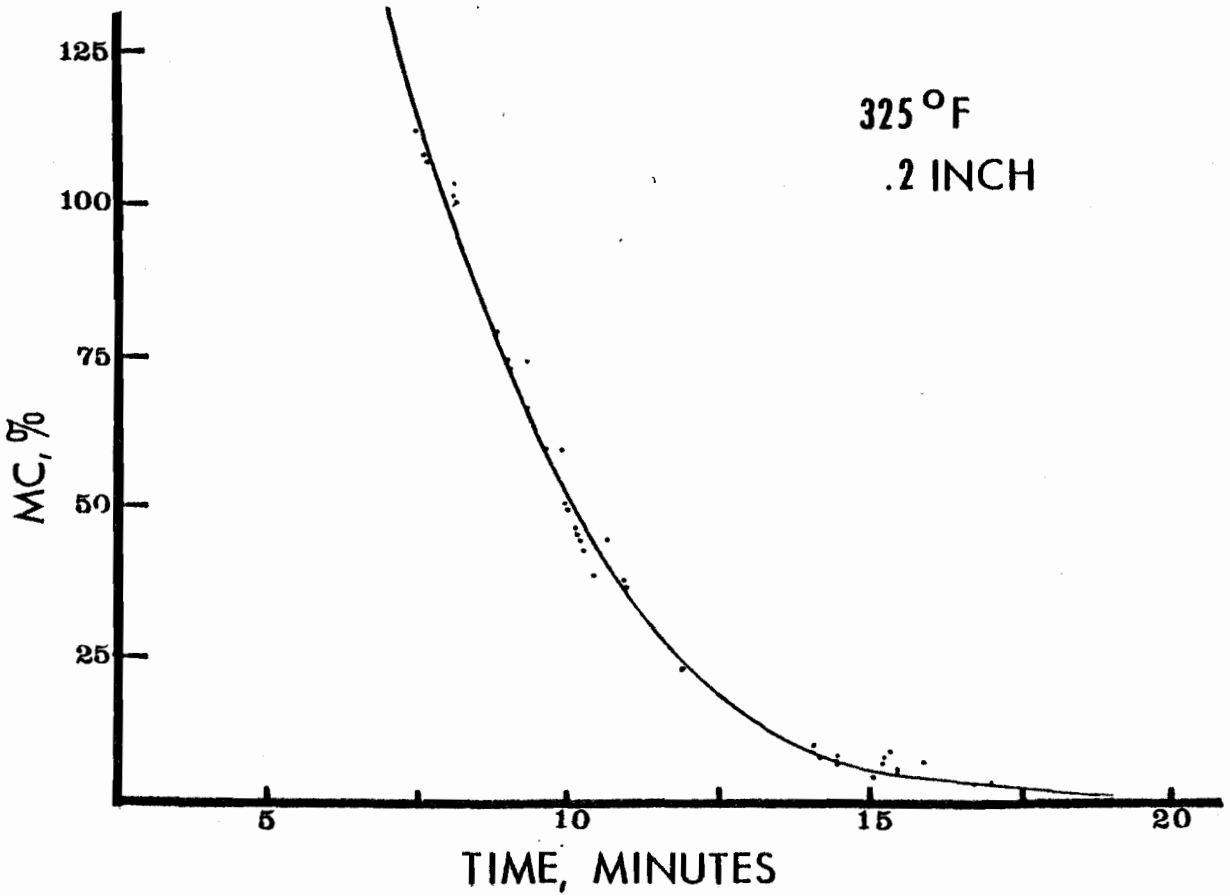
TIME, MINUTES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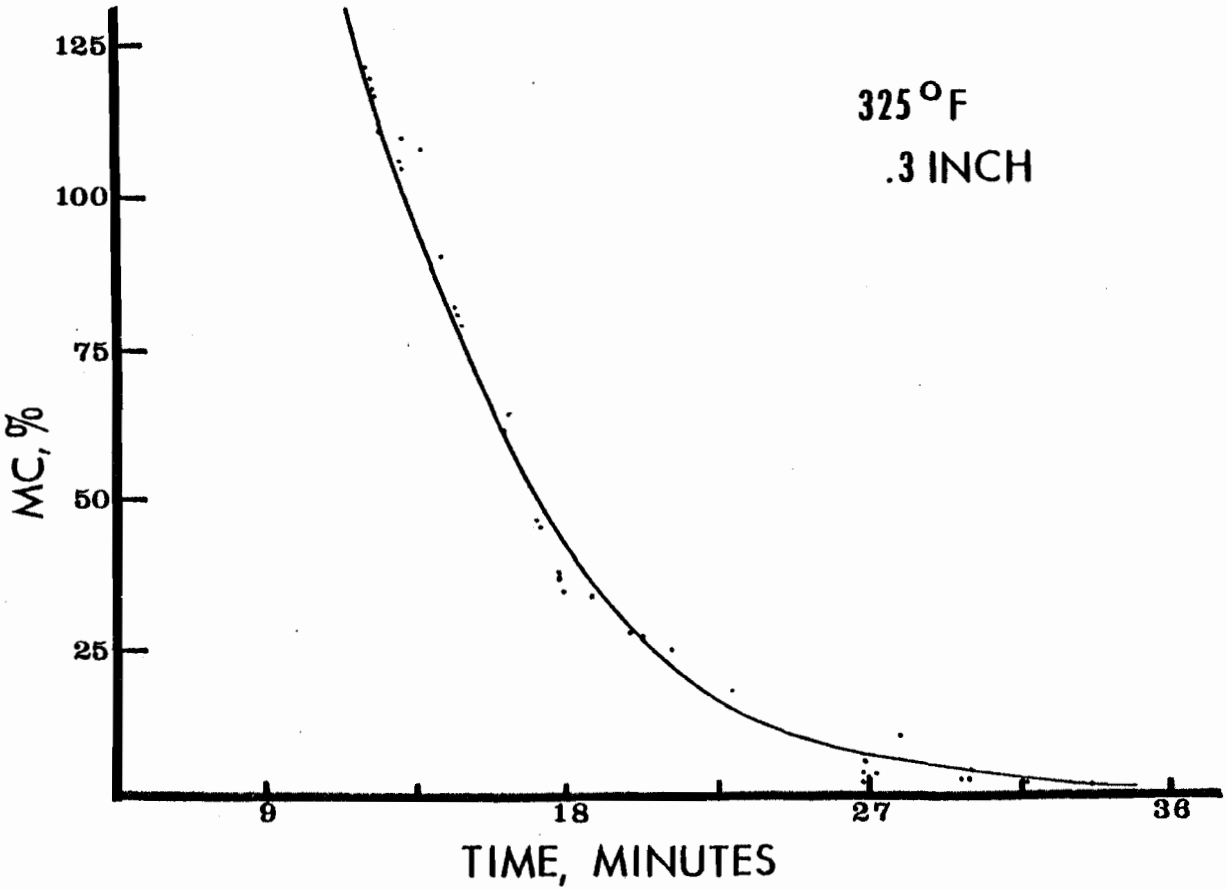
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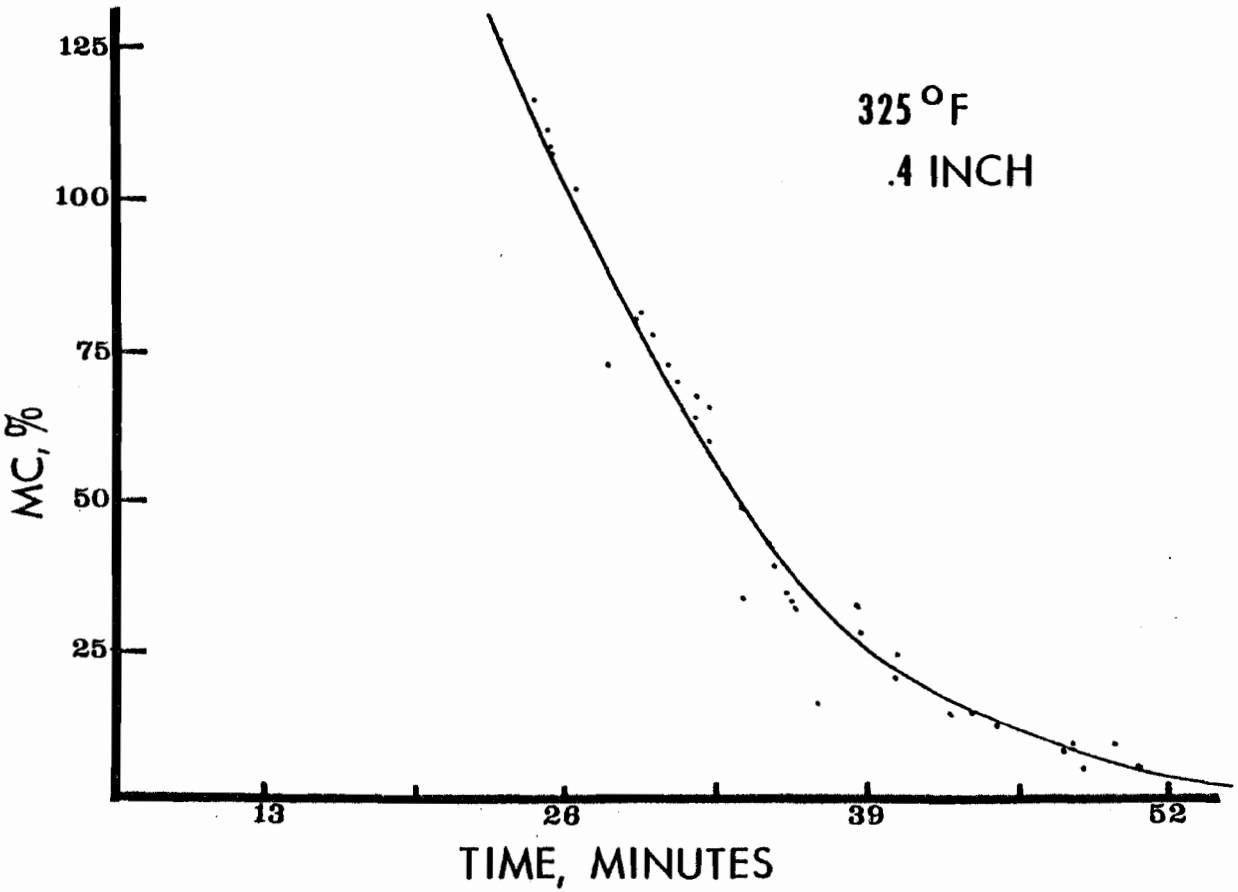
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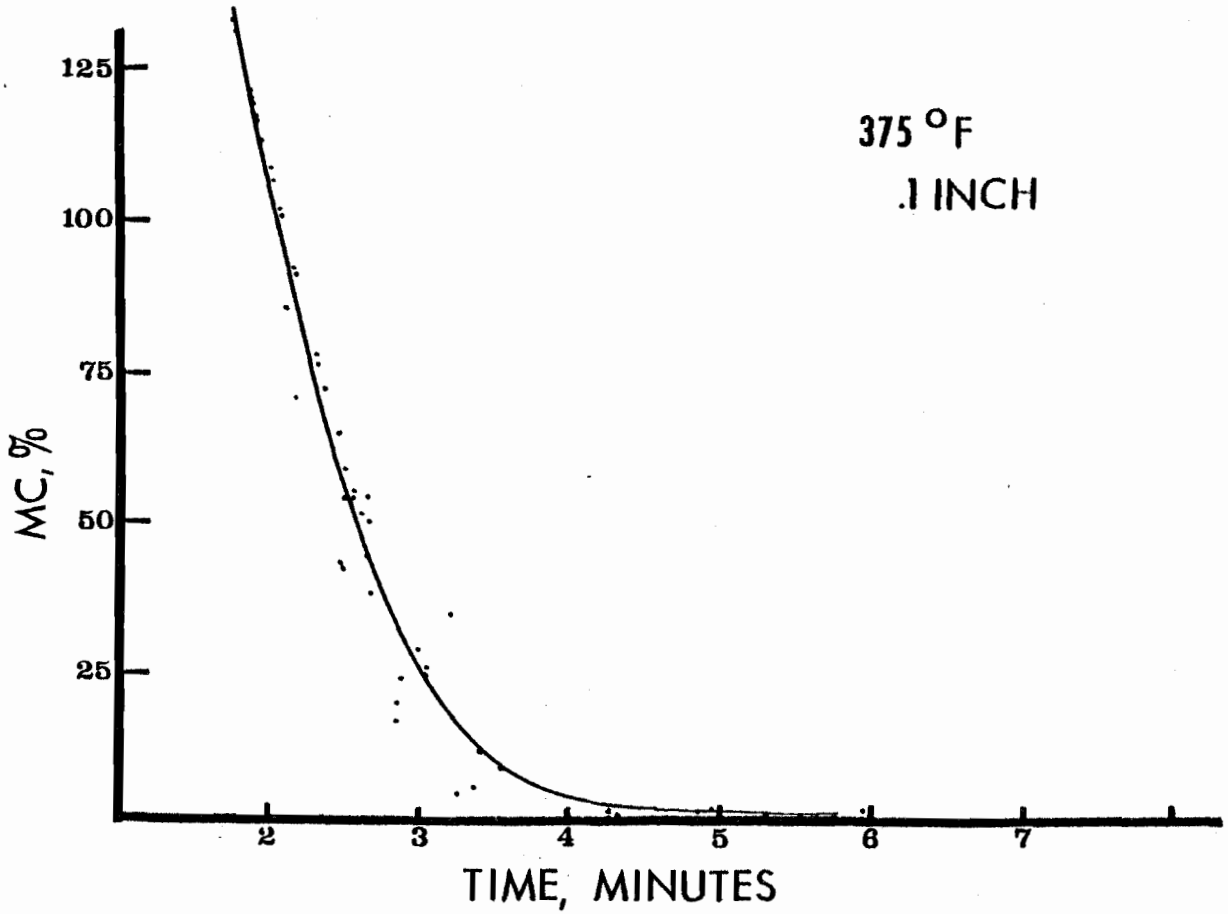
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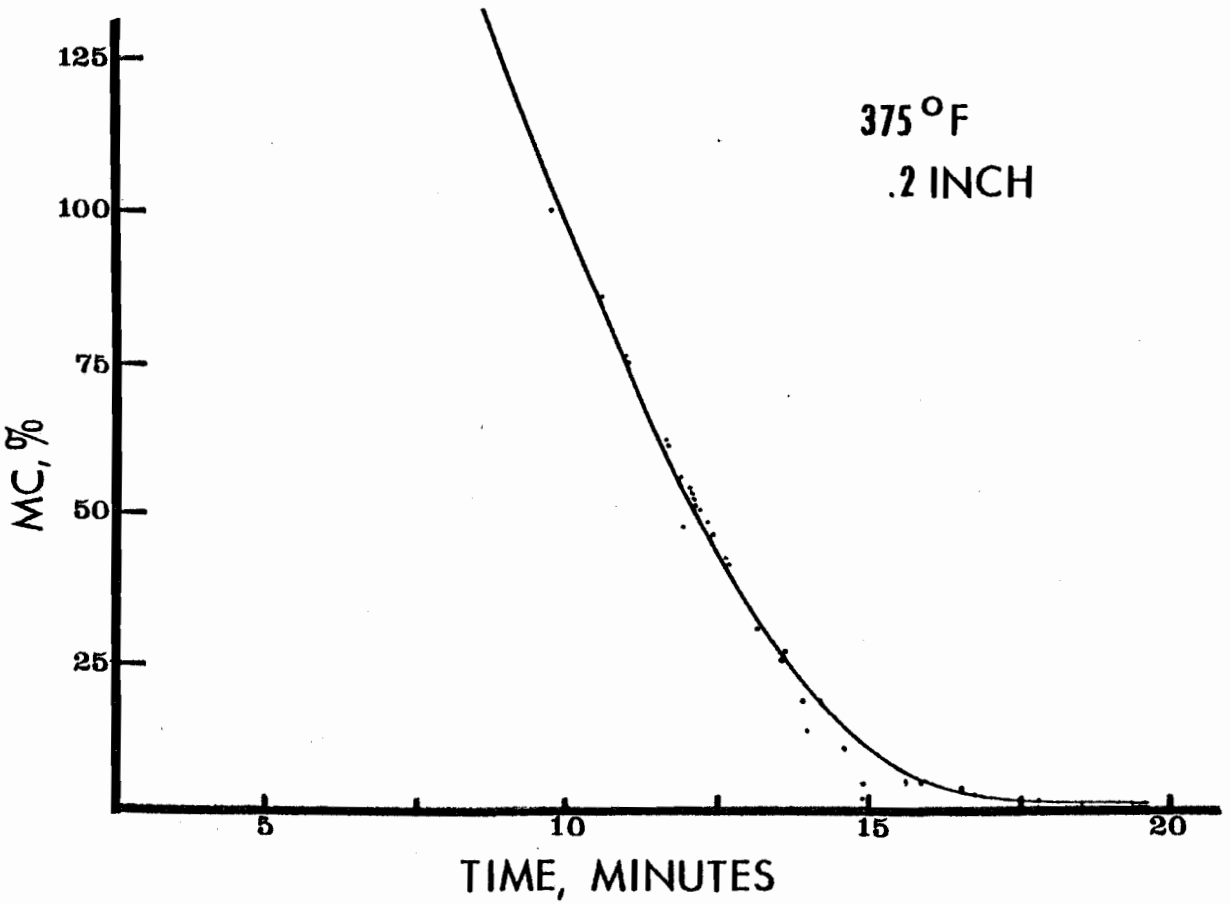
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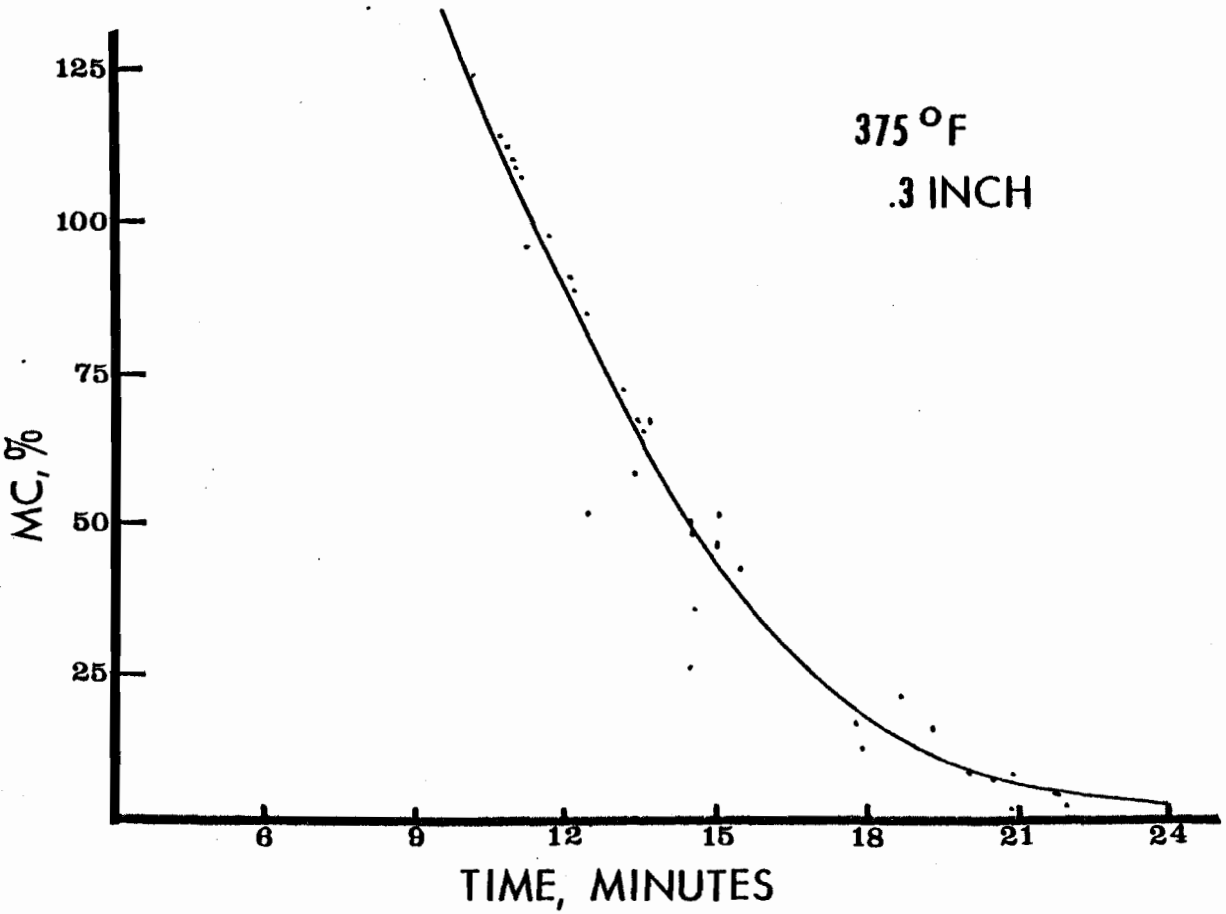
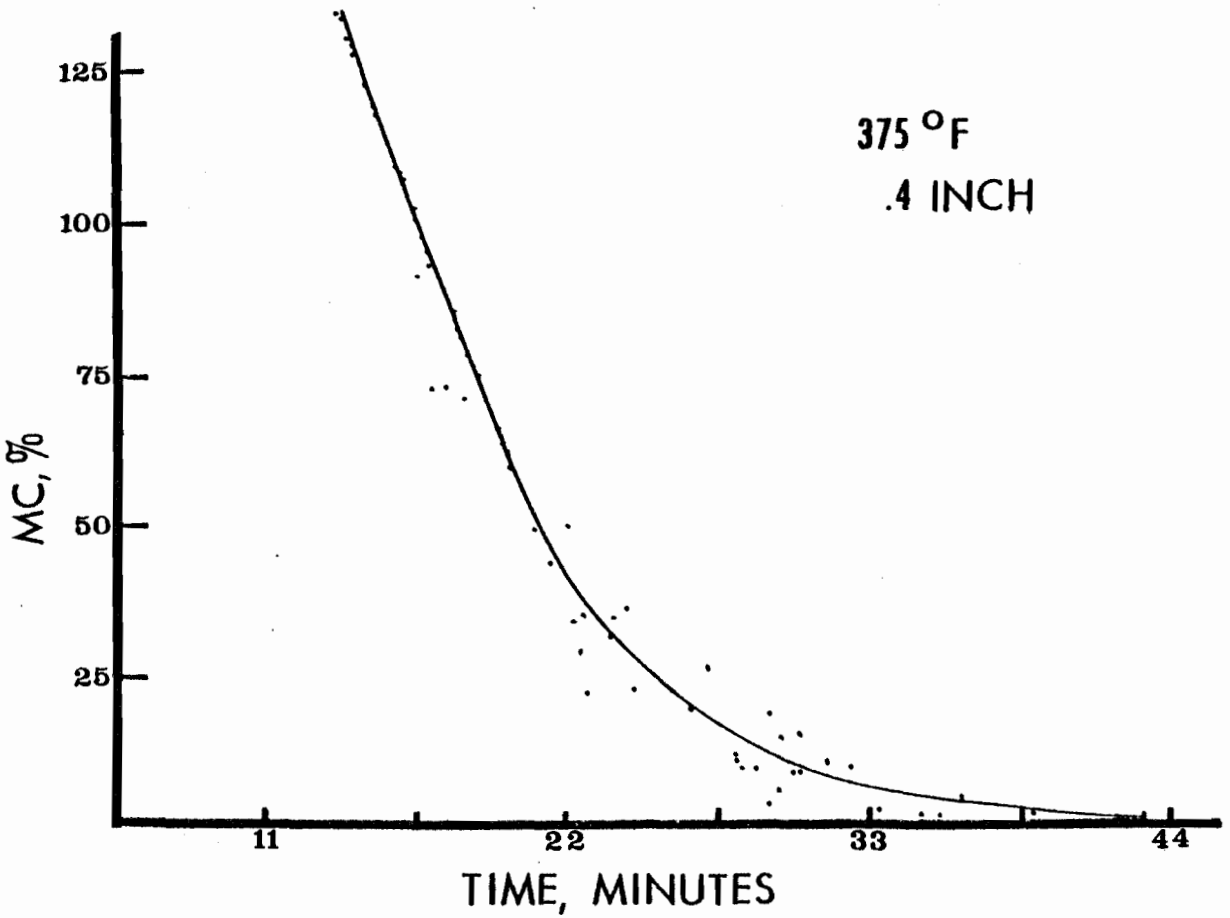
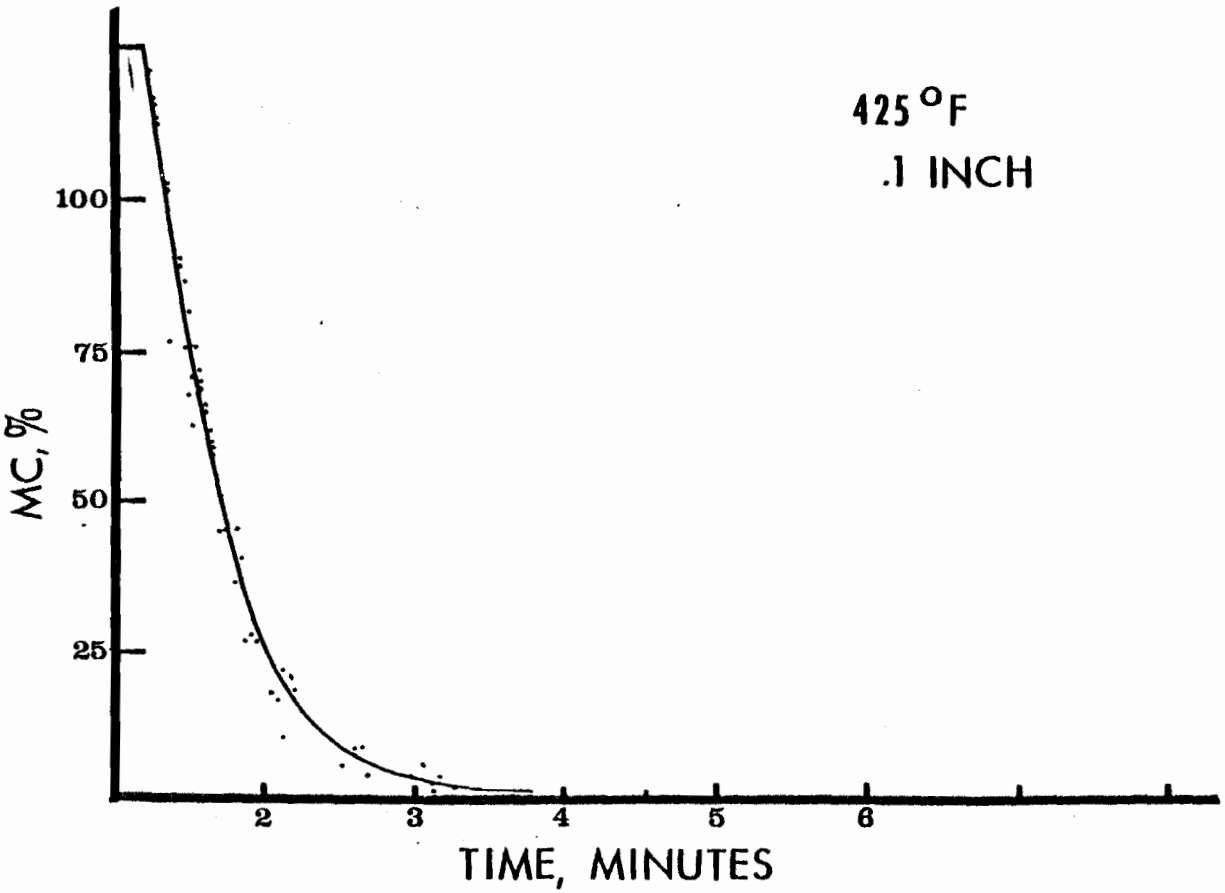
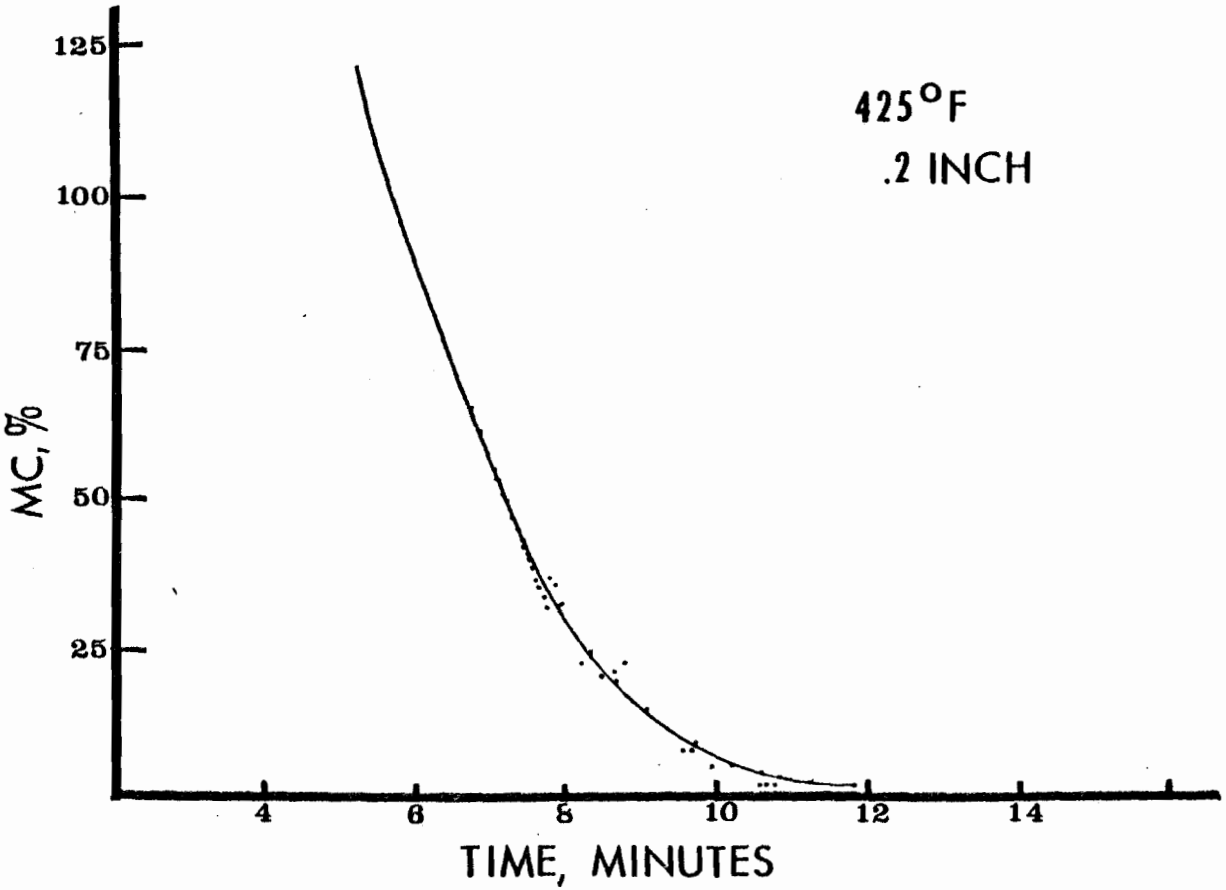
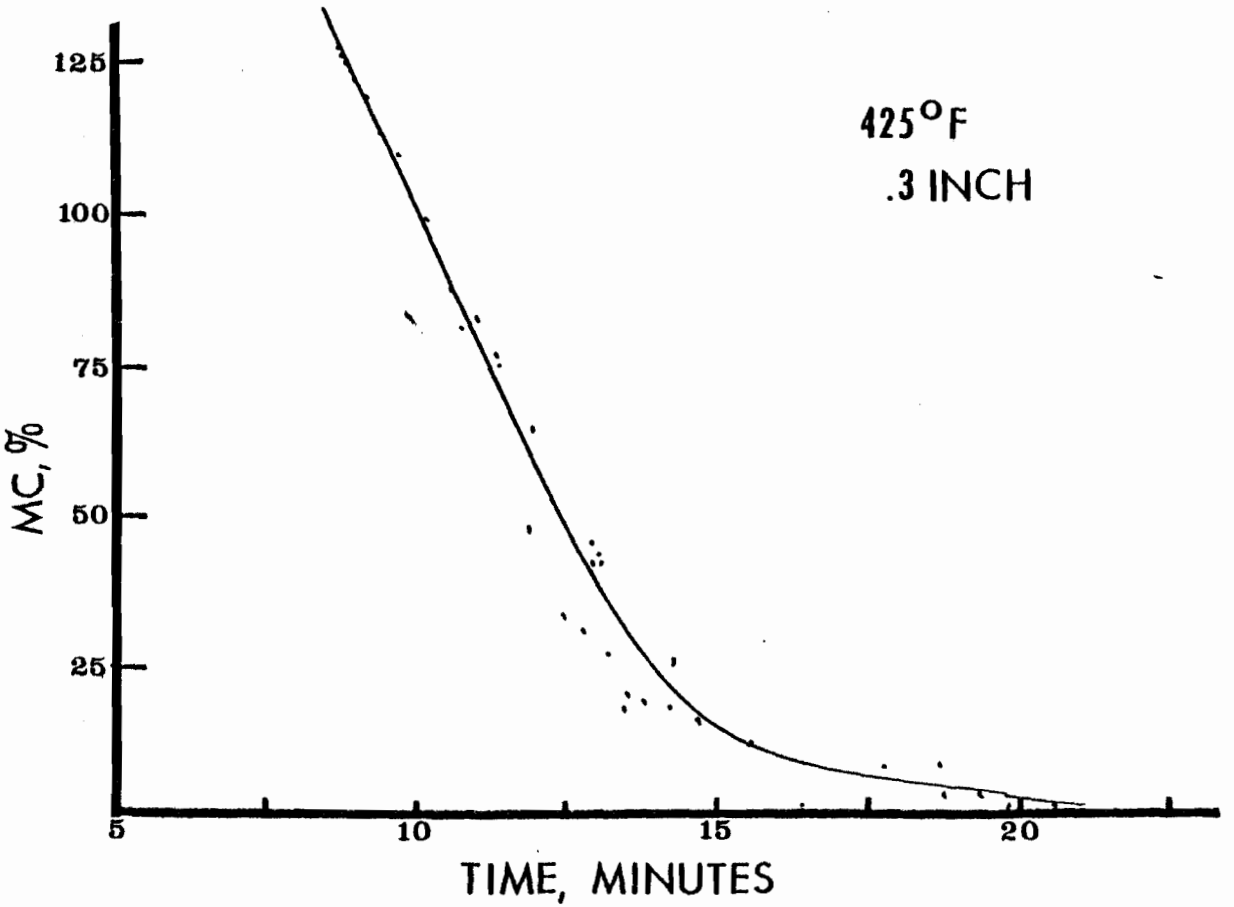
20
TIME, MINUTES

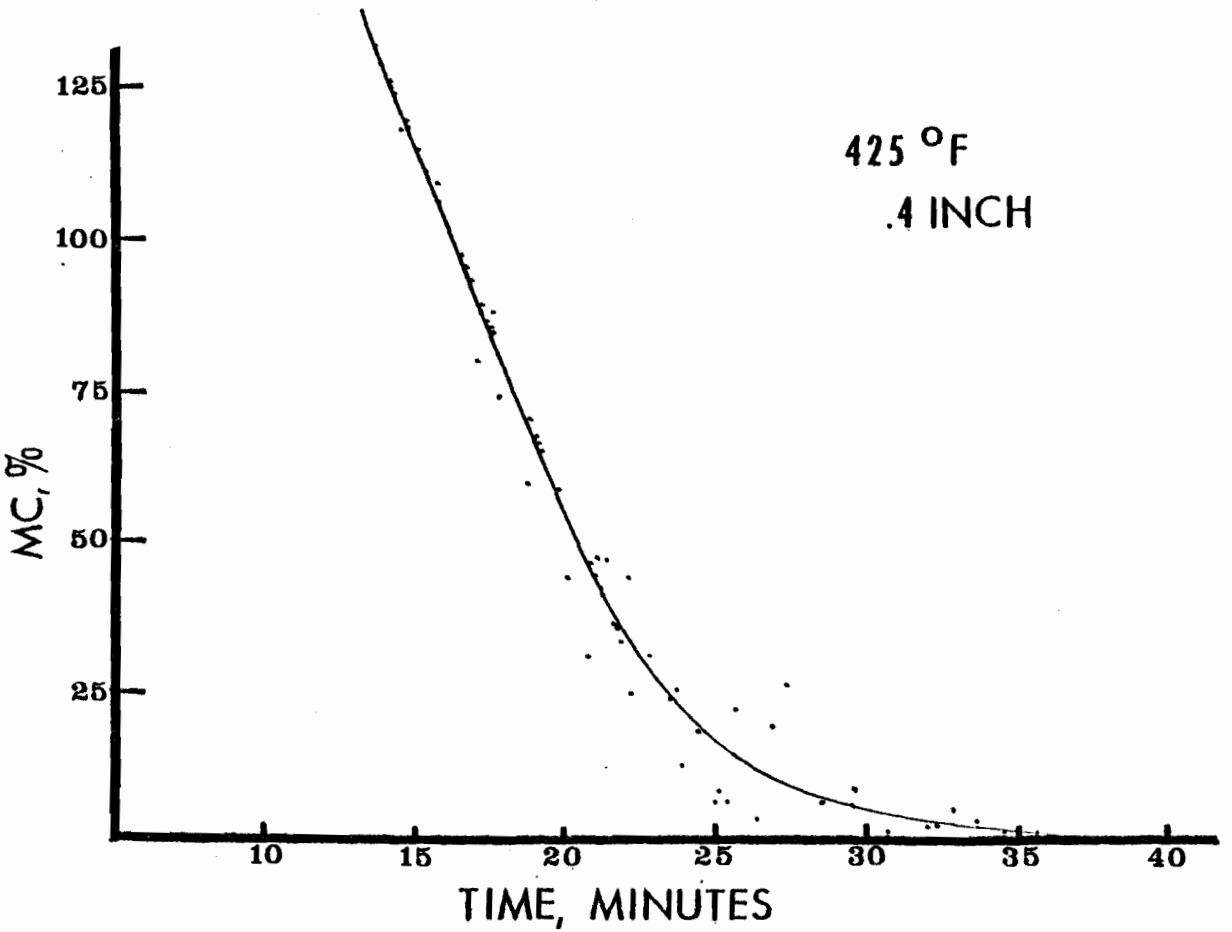

375 °F
.3 INCH
125
100
75
50
25
MC, %
6
9
12
15
18
21
24
TIME, MINUTES

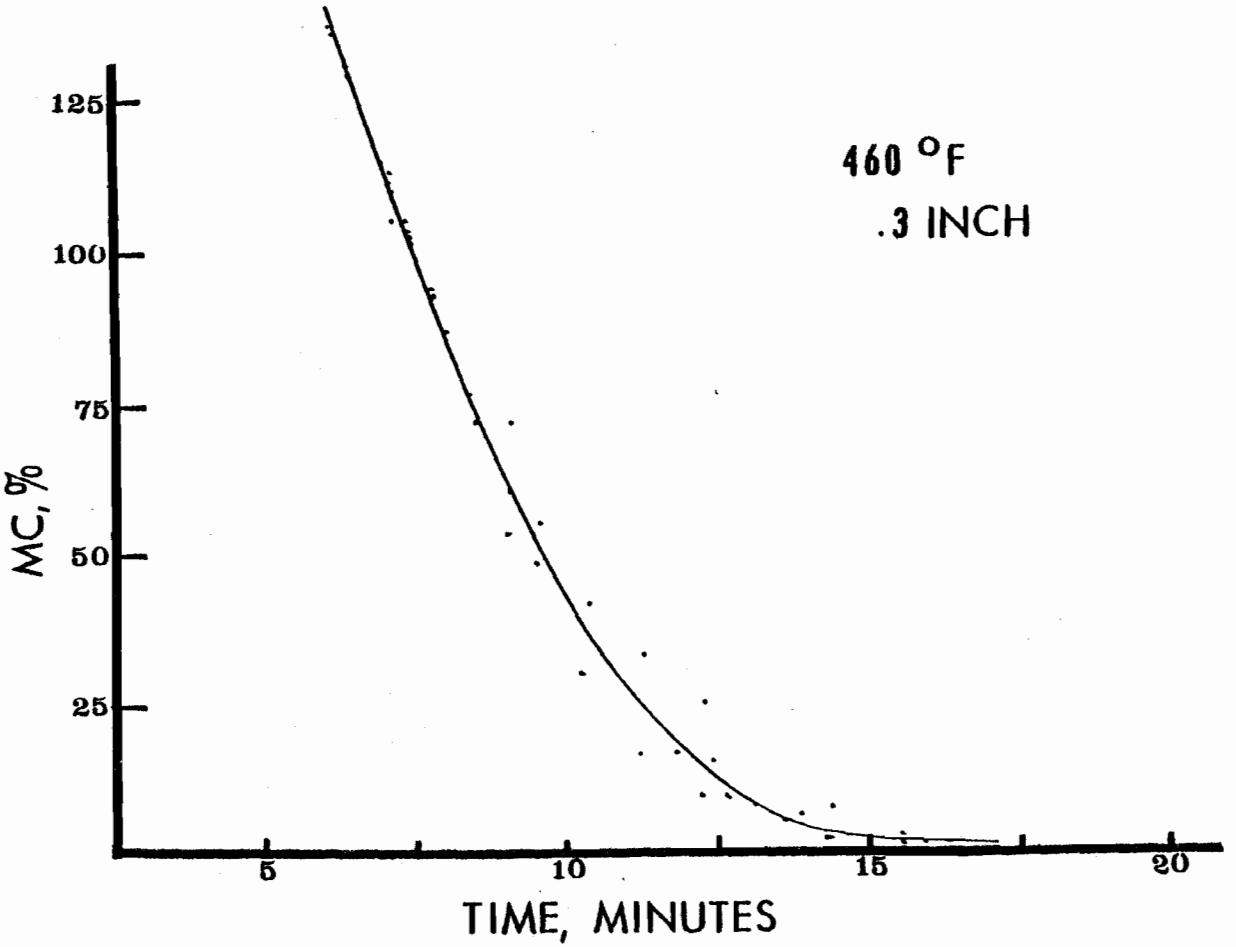

375 °F
.4 INCH
125
100
75
50
25
MC, %
11
22
33
44
TIME, MINUTES

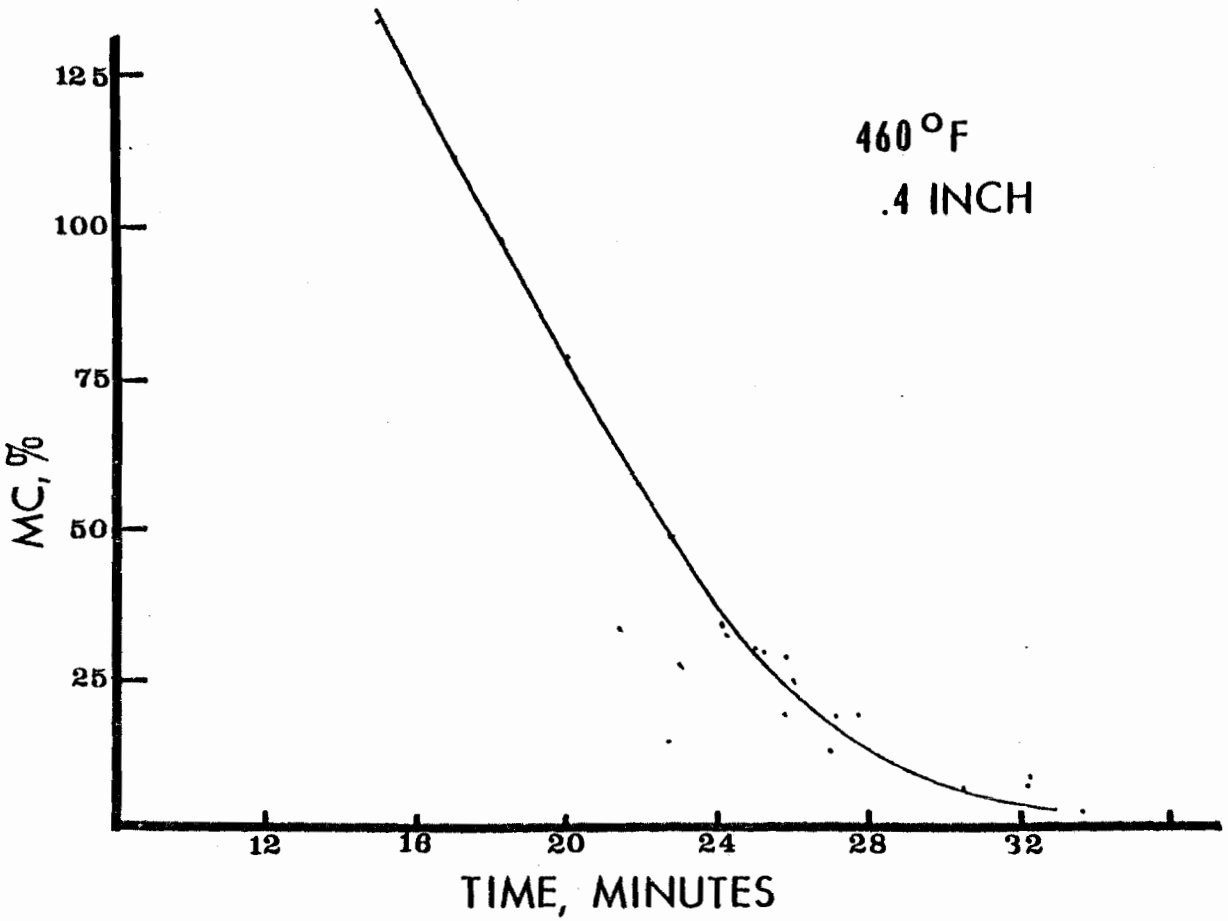

425 °F
.1 INCH
100
75
50
25
MC, %
2
3
4
5
6
TIME, MINUTES


425°F
.2 INCH
MC, %
125
100
75
50
25
4
6
8
10
12
14
TIME, MINUTES


425°F
.3 INCH
MC, %
125
100
75
50
25
5
10
15
20
TIME, MINUTES


425 °F
.4 INCH
MC, %
125
100
75
50
25
10
15
20
25
30
35
40
TIME, MINUTES


460 °F
.3 INCH
125
100
75
50
25
MC, %
5
10
15
20
TIME, MINUTES


460°F
.4 INCH
125
100
75
50
25
MC, %
12
16
20
24
28
32
TIME, MINUTES