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Thermal Degradation of Fire-Retardant-Treated Plywood

Development and Evaluation of a Test Protocol

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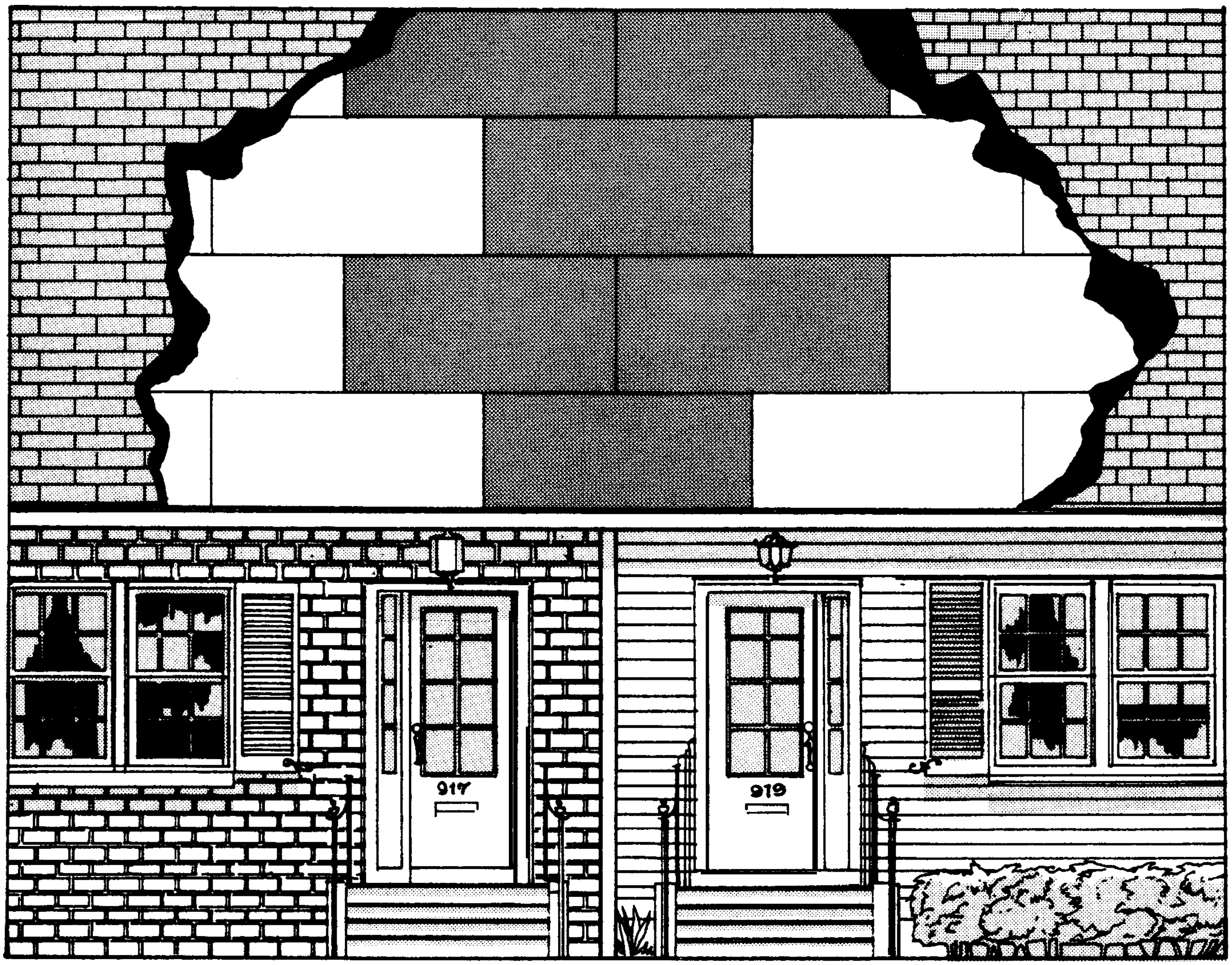

Abstract

Although untreated plywood has given satisfactory performance as roof sheathing for more than 50 years, some fire-retardant-treated plywood products have not performed satisfactorily in recent years. Thermally induced in-service failures have occurred with some fire-retardant-treated plywood roof sheathing. This paper describes the development and evaluation of a new test protocol for screening potential fire retardant treatments for plywood that is continuously or periodically exposed to elevated temperatures.

In the protocol, untreated and monoammonium-phosphate-treated Southern Pine plywood specimens were exposed to various exposure temperatures and durations under steady-state environments of 130°F (54°C)-73 percent relative humidity (RH), 150°F (65°C)-76 percent RH, 170°F (77°C)-79 percent RH, or 170°F (77°C)-50 percent RH. All specimens were mechanically tested in either bending or tension.

Monoammonium-phosphate-treated plywood had lower bending and tension strength than did untreated plywood at all temperatures. The strength degradation rate of untreated and treated plywood increased as exposure temperature increased and appeared constant for any treatment-temperature combination (that is, linear over time). The strength degradation rate was greater at 170°F (77°C)-79 percent RH than at 170°F (77°C)-50 percent RH for both untreated and treated plywood. Within the RH limits studied, the magnitude of the RH effect did not appear to be as influential as the temperature effect. The results indicate the protocol provides an effective screening method for comparing the effects of extended exposure to elevated temperature on strength of untreated plywood and plywood treated with commercial fire-retardant formulations.

Keywords: Plywood, roof sheathing, mechanical properties, strength effects, temperature, thermal effects, treatment, fire retardants

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Introduction

For more than 50 years, untreated and fire-retardant- (FR-) treated lumber and plywood have been successfully used in structures exposed at or near room temperature. We know of no practical in-service strength reductions in that exposure. Untreated plywood also has a long record of adequate performance when used as roof sheathing. Since the early 1960s, FR-treated plywood and lumber have been used in the roof structures of commercial buildings on a limited scale. However, 10 years ago, two major model building codes allowed the use of FR-treated plywood roof sheathing as a replacement for noncombustible deck and parapet-wall systems in some multifamily structures. In addition, at the time the codes were changed, several FR formulators changed their chemical formulation. In the past decade, a number of roof failures have occurred in structures having some type of FR-treated plywood used as roof sheathing (APA 1989a).

Roof sheathing is periodically exposed to temperatures as high as 175°F (80°C) (Heyer 1963, APA 1989b). Temperature has been shown to be a primary factor in strength loss of FR-treated wood, be it initial strength loss (Gerhards 1970, Winandy and others 1988) or in-service strength loss (LeVan and others 1990). The FR-treated roof sheathing that undergoes in-service thermal degradation usually exhibits several classic visual characteristics. Degraded plywood roof sheathing darkens in color, exhibits a dry-rotted-like appearance, crumbles easily when abraded, and often exhibits excessive cross-grain checking. However, the sheathing does not necessarily exhibit each of these characteristics.

Objective

This report describes the development and evaluation of a test protocol for assessing thermally induced strength loss of FR-treated plywood. The protocol was developed to screen potential commercial formulations that are intended for FR treatments of structural plywood used in environments continuously or periodically exposed to elevated temperatures. The protocol was developed because no standardized comparative procedure exists. This protocol provides a laboratory method for comparing treated plywood products to untreated plywood, which has been proven to be satisfactory for structural roof sheathing. Many hypothesis were evaluated during the 2-year evolution of the final protocol. In this report, the background information and test results used to develop the final protocol will be discussed. That test protocol is currently being considered as an Emergency Standard by Subcommittee D07.06 of the American Society for Testing and Materials (ASTM).

This paper is dedicated to the memory of Dr. John J. "Jack" Kozak, our friend and coworker.

Background

Fire-retardant treatments can affect the strength of wood both at the time of processing and while the wood is in service. Initial processing effects are related to treatment and redrying conditions. Secondary effects are associated with in-service exposure of the treated wood to elevated temperatures.

Initial Processing Effects

The work of many investigators has indicated that FR treatments initially reduce strength of lumber and plywood 10 to 25 percent. The magnitude of strength reduction depends on the FR chemical, the severity of treatment and processing conditions, and the wood property under consideration. Taken as a whole, the literature has shown that the temperature used in kiln drying FR-treated lumber and plywood after treatment is one of the factors responsible for the magnitude of initial strength reduction. Accordingly, American Wood Preservers' Association Standards C-20 (for FR-treated lumber) and C-27 (for FR-treated plywood) both require that the kiln temperature after treatment be limited to ≤160°F (≤71°C) until the average moisture content of the FR-treated material is below 25 percent (AWPA 1990a,b). In general, these initial processing effects can be and are accommodated within existing design procedures.

Secondary In-Service Effects

The FR treatments generally lower the thermal degradation temperature of most wood-based materials (LeVan 1984). When some FR formulations are exposed to elevated temperatures, such as when treated wood is used as roof sheathing, thermally induced strength reductions can occur in service. Recent reports have described strength reduction of FR-treated plywood roof sheathing (LeVan and Collet 1989), thermochemical factors (LeVan and Winandy 1990), and design guidelines (Winandy 1990).

In a recent study of six generic FR formulations in small clear wood specimens, the long-term effects of steady-state exposure for 6 months at 130°F (54°C)-73 percent relative humidity (RH) were found to be negligible (LeVan and others 1990). However, the bending strength of all treated specimens and the untreated control was reduced after 6 months of exposure at 180°F (82°C)-50 percent RH. After thermally induced strength loss had been initiated, the rate of strength loss over time of exposure was similar between the FR-treated and untreated materials. Thus, the real differences between the performance of FR chemicals studied were the magnitude of the initial strength effect and the duration of elevated temperature exposure required to initiate secondary strength effects.

Rationale

The final protocol represents the cooperative effort of many persons (Table 1). The protocol evolved over a 2-year technical assessment that addressed key questions about the scope, design, and accuracy of the proposed test method. These questions identified

1. wood species, plywood quality, and specimen size,
2. mechanical properties,
3. simulation of field conditions in the laboratory,
4. exposure temperature, humidity and duration, and
5. experimental design considerations.

We will discuss the rationale underlying many of the experimental design decisions and the adaptation and refinement of the initial experimental techniques for the final test protocol.

Species, Plywood Quality, and Specimen Size

Southern Pine is probably the most popular plywood species grouping for use with fire retardants because of its low cost and superior treatability. It is also the most readily available wood for the Eastern Seaboard market where building codes allow the use of FR-treated plywood. Accordingly, FR-treated Southern Pine plywood is also the material that has undergone the most problems with in-service strength loss. For these reasons, Southern Pine plywood was selected as the material most appropriate for the test protocol.

Because our objective was to develop a comparative procedure rather than to establish design values, N-grade plywood was chosen to eliminate the uncontrollable influence of knots and voids. The 4- by 8-ft (1.22- by 2.44-m) plywood panels used in developing the test protocol were special lay-ups of all N-grade veneers (U.S. Department of Commerce 1983). The N-grade veneer is the highest quality specified in PS-1-83, the Plywood Products Standard. This grade allows no knots or voids, allows no splits >0.06 in. (>1.6 mm), and limits nonoverlapping repairs (e.g., patches) to <0.98 in. (<25 mm) wide and <3.5 in. (<89 mm) long. The decision to use N-grade plywood presumed that comparative estimates of relative thermal effects based on high-quality material are representative of field effects with commercial panels. Subsequent work at Forest Products Laboratory (FPL) is examining that hypothesis.

Table 1—Task group responsible for developing test protocol

Name	Affiliation
Craig R. McIntyre, Chairman	Hickson Corporation
Kendall H. Bassett	Weyerhaeuser Company
Thomas R. Flint	American Plywood Association
Scott P. Hoffman	Hickson Corporation
Barry W. Holden	Hoover Treated Wood Products, Inc.
Edward G. King, Jr.	Wood Construction Technologies, Inc.
John J. Kozak[a]	Osmose Company
Joseph J. Kusar[b]	Tolleson Lumber Company
Alan L. Lambuth	Boise-Cascade, Inc.
Susan L. LeVan	Forest Products Laboratory'
William S. McNamera	Osmose Company
Fred L. Omundson	CSI, Inc.
Kenneth R. Peterson	Georgia-Pacific, Inc.
Nicholas V. Poletika	J.H. Baxter, Inc.
Alan F. Preston	CSI, Inc.
David M. Roberts	CSI, Inc.
Robert J. Ross	Forest Products Laboratory[c]
Gerald E. Sherwood	National Forest Products Association
Glenn A. Wilson	Hoover Treated Wood Products, Inc.
Jerrold E. Winandy	Forest Products Laboratory[c]
Steven C. Zylkowski	American Plywood Association

[a] Deceased.
[b] Initial Task Group Chairman, from December 1987 to October 1989.
[c] USDA Forest Service, Madison, Wisconsin.

Early in the development of the protocol, the task group considered the size of test specimens. Capacity of available environmental chambers, economic considerations, and intended use of the protocol as a comparative procedure (rather than a design-setting procedure) were all considerations. These considerations dictated the use of small specimens rather than full-size panels. Mechanical property estimates based on results from small, defect-free specimens cut from full-size panels usually do not precisely predict the properties of full-size panels because of knots and voids within the panels. McNatt (1984) studied the accuracy of property estimates for large plywood panels based on small specimen results. He found that modulus of elasticity (MOE) values of small specimens were usually 10 to 20 percent lower than MOE values of full-sized panels; modulus of rupture (MOR) values of small specimens were usually 6 to 30 percent greater than MOR values of full-sized panels. McNatt and others (1990) also presented a series of predictive equations that allow prediction of full-sized panel properties from small specimen data. Based on this information, the task group decided that 3-in.-wide by 24-in.-long (75-mm-wide by 610-mm-long) (face veneer parallel to long axis) bending specimens provided repeatable estimates of material properties, as well as a workable specimen size.

Mechanical Properties

Bending properties were evaluated because bending loads were considered critical for plywood roof sheathing. The effects of extended exposure at elevated temperature on the tensile properties of FR-treated plywood were also studied because we anticipated a differential effect between bending and tensile properties. A cutting procedure was chosen that provided an equal number of bending and tensile specimens. This cutting format provided 20 bending and 20 tensile specimens per exposure combination (treatment-temperature-humidity-exposure duration).

Laboratory Simulation of Field Conditions

Plywood roof sheathing is exposed to a constantly changing environment. Solar radiation causes roof sheathing to heat up and cool on a daily cycle. Roof sheathing moisture content follows an opposite cycle. Temperature increases during the day tend to dry roof sheathing, and cooler evening temperatures can cause moisture adsorption. Seasonal cycles occur as well. Changes in moisture content are predominantly controlled by seasonal rather than daily conditions because wood has a relatively low moisture diffusion coefficient. Ideally, an optimum laboratory exposure technique would mimic these cyclic patterns of temperature and relative humidity. However, such a simulation would tend to last many years and to be prohibitively expensive. Accelerated cyclic environments were considered to speed the process, but the time required was still prohibitive.

The final laboratory exposure technique considered was steady-state, elevated temperature exposure. This exposure is fast and it indicates whether particular chemicals are activated at the tested temperature. Steady-state exposure at elevated laboratory conditions was chosen as the most reasonable compromise between time, cost, and the need for reliable data on comparative performance.

The task group recognized that any laboratory exposure scenario has problems because of a lack of constitutive relationships between laboratory and field (in-service) conditions. The relationships between cumulative thermal-moisture exposure and strength loss over time for both laboratory and in-service exposures will need to be developed to obtain reliable in-service predictive capability from laboratory tests. Future research will address these needs.

Exposure Conditions

The protocol was not intended to predict roof sheathing performance exactly. Rather, the intention was to produce comparative data of the response of treated and untreated plywood to elevated thermal conditions. The task group decided that data would be needed for three critical temperatures: 130°F, 150°F, and 170°F (54°C, 65°C, and 77°C). These temperatures respectively represent a daily temperature commonly obtained in plywood roof sheathing, a critical temperature limit for long-term exposure of wood products (NFPA 1986), and a periodically obtained daily maximum temperature (Heyer 1963, APA 1989b).

Because acid-catalyzed dehydration reactions are believed to be the primary mechanism of strength loss (LeVan and Winandy 1990), plywood moisture content exaggerates the thermal degradation process. Thus, the protocol needed to take into account the effect of moisture. The task group collectively thought that plywood roof sheathing would vary on a seasonal basis between 6 percent and 12 percent equilibrium moisture content assuming the presence of an attic with near code-specified ventilation and a well-constructed roofing membrane. Therefore, two matched 170°F (77°C) exposures were performed, one at 79 percent RH and the other at 50 percent RH. The first exposure produces 12 percent equilibrium moisture content in untreated wood and the second 6 percent equilibrium moisture content in untreated wood (Forest Products Laboratory 1987).

Duration of exposure was another important variable. The task group recognized that 170°F (77°C) would induce a given strength reduction in a shorter period than would 130°F (54°C). However, the question of a thermal threshold, below which little practical thermally induced strength reductions would occur, needed to be addressed. Thus, lower temperature exposures were run for a progressively longer time. The 170°F (77°C) exposures ran for 63 days, the 150°F (65°C) exposures for 112 days, and the 130°F (54°C) exposures for 140 days.

Experimental Design

Wood is a variable material. The mechanical properties of specimens from a single plywood panel generally tend to have less variability among themselves than do specimens cut from two different panels. Distinguishing within-panel variability from between-panel variability can greatly increase the sensitivity of statistical analysis. Statistical designs that use the technique of segregating independent variabilities are known as blocked designs (Snedecor and Cochran 1967). However, it is sometimes more efficient to increase the number of specimens used in an experiment than to control unspecific variability. To determine the actual benefits of blocking, we compared two methods of assigning specimens to experimental groups. In the first method, specimens were allotted to the groups by way of a random-shuffle technique. The second method used a blocked experimental design. In this method, the specimens were assigned to experimental groups in a predesignated manner so that each group was allotted only two specimens from any single panel of plywood.

Each 0.625-in.- (15.9-mm-) thick Southern Pine panel (4 by 8 ft (1.22 by 2.44 m)) was cut into four 4- by 2-ft (1.22- by 0.61-m) sheets. For each panel, two sheets were arbitrarily kept as untreated controls and two sheets were pressure treated in a laboratory cylinder at the Hickson Corporation Research and Development Center. An 8.3-percent solution of technical grade monoammonium phosphate (MAP) in water was used to achieve a final retention of 3.15 lb/ft^3 (50.4 kg/m^3) MAP. Experience has shown that this retention provides plywood with a Class A flame-spread rating. All treated specimens were kiln dried at dry-bulb and wet-bulb temperatures of 160°F (71°C) and 150°F (65°C) for 114 h to final average moisture content of 15 percent. Ten bending and 10 tension specimens were cut from each sheet. This procedure provided 20 untreated and 20 treated specimens from each panel for both bending and tension tests. Bending specimens were 3 in. wide by 24 in. long (75 mm wide by 610 mm long). Tensile specimens were 1 in. wide by 24 in. long (25 mm wide by 610 mm long) and necked to 0.5 in. (12.5 mm) over the middle 2.5 in. (6.4 mm). Twenty specimens were allotted to each exposure combination.

Exposure Conditions

Prior to elevated temperature exposure, all specimens were conditioned to constant weight at 74°F (23°C)-65 percent RH, which represents approximately 12 percent equilibrium moisture content conditions for untreated wood (Forest Products Laboratory 1987). Individual groups of specimens were then exposed for designated durations at the controlled, steady-state, elevated temperature-humidity conditions shown in Table 2. After the allotted exposure duration and before mechanical testing, the specimens were again conditioned to constant weight at 74°F (23°C)-65 percent RH.

Table 2—Exposure combinations for test protocol[a]

Temperature (°F (°C))	RH (%)	Design[b]	Exposure (days)	Test mode
80 (27)[c]	30	Random and blocked	0	Bending and tension
130 (54)	73	Random	14, 28, 56, 84, 116, 140	Bending and tension
150 (65)	76	Blocked	7, 14, 28, 56, 84, 112	Bending
170 (77)	79	Random	7, 14, 21, 35, 49, 63	Bending and tension
170 (77)	79	Blocked	7, 14, 21, 35, 49, 63	Bending and tension
170 (77)	50	Random	7, 14, 21, 35, 49, 63	Bending

[a] Same exposure combination were used for untreated and treated specimens. Treatment with monoammonium phosphate (MAP), 3.5 lb/ft^3 (56 kg/m^3).
[b] Specimens allotted to blocked design were tested by Hickson Corporation. All other specimens were allotted to random design and tested at the FPL.
[c] Control.

Mechanical Testing

Mechanical testing in bending followed procedures outlined in ASTM D-3043 Method A (ASTM 1990b). Specimens were center-point loaded using rotational end-supports over a span of 22 in. (560 mm). Rate of loading in bending was 0.2 in/min (5 mm/min). Tension tests followed procedures outlined in ASTM D-3500 Method A, Specimen type B (ASTM 1990c). Rate of loading in tension was 0.04 in/min (0.9 mm/min).

Evaluation

Experimental results are given in Appendix A. Mean trends are shown in Figures 1 to 9.

Experimental Design

Differences between the blocked experimental design and the random design can be evaluated by comparing the two sets of data for the 170°F (77°C)-79 percent RH exposure (Figs. 1, 2). The trend shown by the mean results is similar for MAP-treated and untreated material in tension (Fig. 2) and MAP-treated materials in bending (Fig. 1), but not for untreated materials in bending (Fig. 1). This difference in mean trends between the two experimental designs in bending is probably related not to the experimental design but rather to a difference between the manner in which the two testing laboratories performed the mechanical tests. The bending specimens from the blocked design that were exposed for ≤35 days were loaded until the first major drop in load (crack); the load was then removed. Specimens from the blocked design that were exposed for >35 days and specimens from the random-design were tested in bending until they would no longer support load. Untreated plywood can be extremely tough and durable; with continued loading, the maximum load is sometimes obtained after the first major drop in load. Conversely, treated material in bending and treated and untreated material in tension tend to be more brittle, and the first drop in load is nearly always the maximum sustainable load. Thus, treated material in bending would be less sensitive than untreated material to premature termination of the test. This appears to be the case. Otherwise, mean trends for MOR and UTS are quite similar (Figs. 1, 2).

The efficiency in analysis of wood mechanical property data from blocked experimental designs is usually greater than that from random designs if sufficient degrees of freedom exist in the overall experimental design. Recall that overall standard error is represented by the standard deviations listed (Appendix A, Tables A1 to A9). Also recall that for data from the blocked design, a portion of that overall standard error can be specifically attributed to panel-to-panel variability and the remainder attributed to within-panel variability. To evaluate this, we performed an analysis of variance on the blocked experimental results assuming a (1) random and (2) blocked design. We found that the specific partitioning of standard error in the blocked design effectively minimized the least significant difference calculated from the blocked design by approximately 6 to 8 percent when compared to the random design. Based on this information, we decided that a blocked experimental design was the preferable methodology.

Exposure Conditions

Bending and tensile strength degradation of treated plywood was related to exposure temperature, duration of exposure, and relative humidity (Tables A1 and A2). We also examined the effect of wood specific gravity and moisture content on wood degradation.

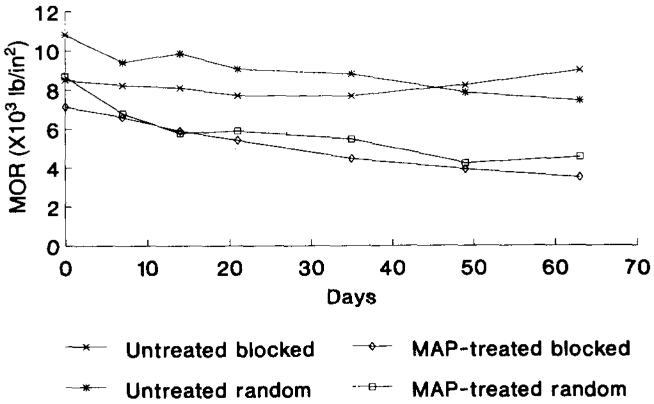

Figure 1—Effect of 170°F (77°C)-79 percent RH exposure on modulus of rupture (MOR). 1 lb/in² = 6.89 kPa.

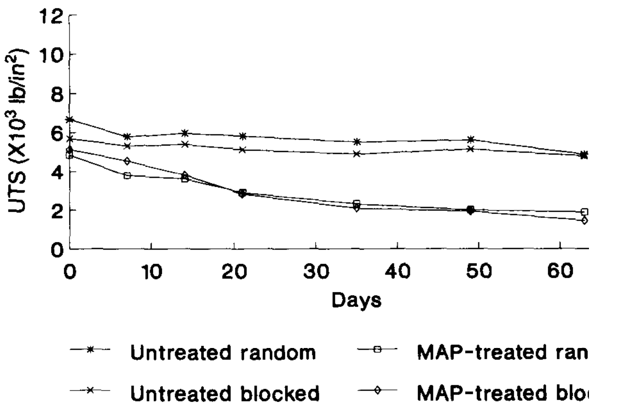

Figure 2—Effect of 170°F (77°C)-79 percent RH exposure on ultimate tensile stress (UTS). 1 lb/in² = 6.89 kPa.

Temperature

As exposure temperature and duration increased, mechanical properties generally decreased. Examples of these relationships are shown for MOR and ultimate tensile stress (UTS) of untreated plywood exposed at 130°F (54°C)-73 percent RH, 150°F (65°C)-76 percent RH, and 170° (77°C)-79 percent RH (Figs. 3, 5) and for MOR and UTS of MAP-treated plywood (Figs. 4, 6) (Tables A3 to A6). These data show four trends:

1. Strength of MAP-treated plywood was initially reduced compared to that of untreated plywood.
2. Effect of temperature on MOR of untreated and MAP-treated plywood was generally similar to that on UTS.
3. Rate of strength degradation (as shown by general slope in strength over time relationship) was directly related to exposure temperature.
4. Rate of degradation over duration of exposure in both bending and tensile strength generally appeared constant for any exposure combination.

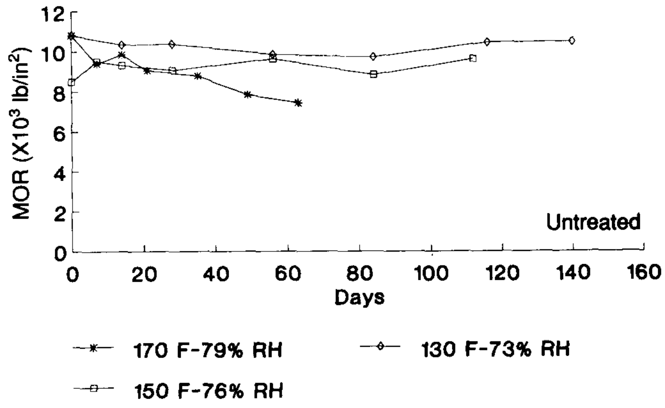

Figure 3—Effect of exposure to various temperatures on modulus of rupture (MOR) of untreated plywood. 1 lb/in² = 6.89 kPa.

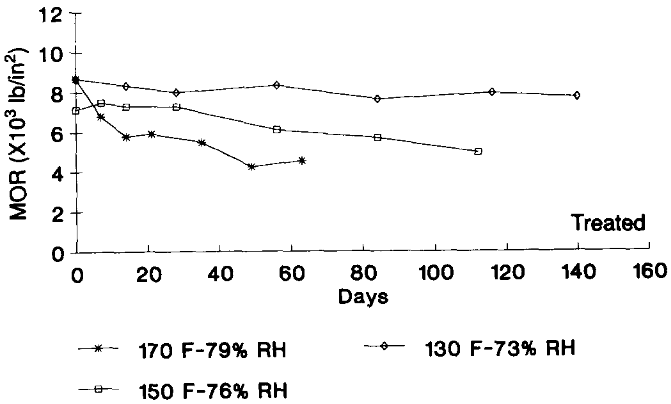

Figure 4—Effect of exposure to various temperatures on modulus of rupture (MOR) of MAP-treated plywood. 1 lb/in² = 6.89 kPa.

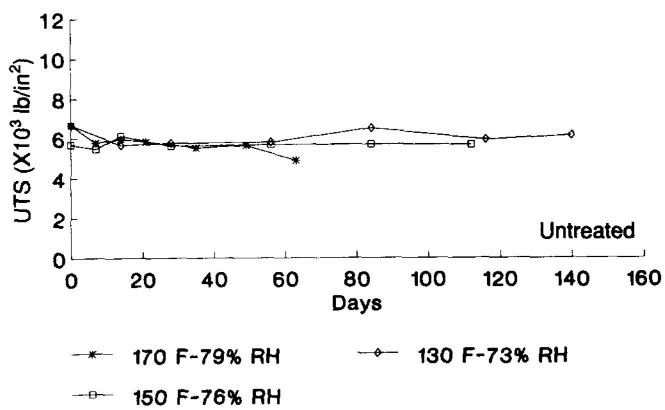

Figure 5—Effect of exposure to various temperatures on ultimate tensile stress (UTS) of untreated plywood. 1 lb/in² = 6.89 kPa.

Although linear (first-order), second-order, and several independent-variable transformations were considered, none seemed to substantially fit the data better than the linear model. Thus, a first-order model was

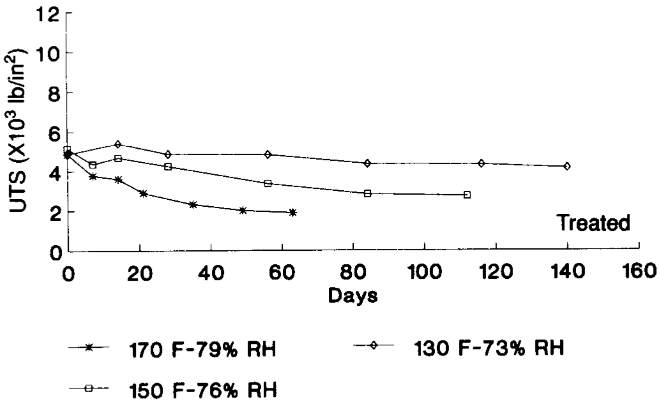

Figure 6—Effect of exposure to various temperatures on ultimate tensile stress (UTS) of MAP-treated plywood. 1 lb/in^2 = 6.89 kPa.

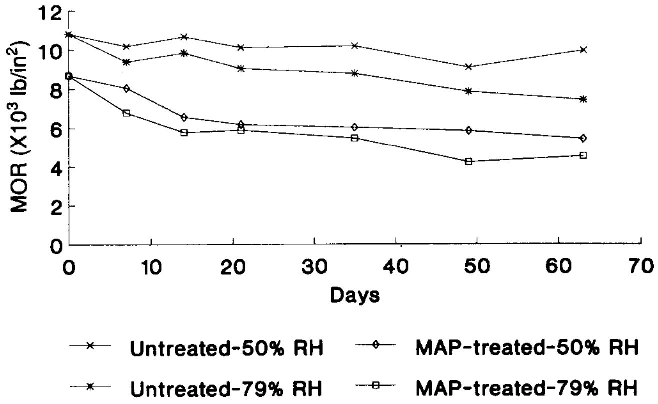

Figure 7—Effect of exposure to 170°F (77°C) at different relative humidities on modulus of rupture (MOR) of untreated and MAP-treated plywood. 1 lb/in^2 = 6.89 kPa.

selected because of its simplicity. A linear or first-order relationship was noted for a parallel study conducted simultaneously using untreated specimens, MAP-treated specimens, and specimens treated with several other FR formulations (LeVan and others 1990).

The rate of strength degradation over duration of exposure generally appears to be a function of exposure temperature (Figs. 3 to 7). Specifically, the data for treated material seem to refute the existence of a temperature threshold, below which thermally induced degradation does not occur and above which permanent thermally induced degradation does occur. This would imply that the performance of a treated product after an extended period at some elevated temperature can be used to predict laboratory performance at higher or lower temperatures. Thus, we believe that running the thermal exposures at 170°F (77°C)-67 percent RH over an extended period of at least 175 days is sufficient to indicate products or treatments that are susceptible to thermally induced degradation.

Relative Humidity

Increasing the RH increased the moisture content of untreated or MAP-treated plywood. The increase in moisture content, in turn, increased the rate of thermally induced strength loss over the duration of exposure at 170°F (77°C) (Fig. 7). A comparison of untreated and MAP-treated plywood exposed at 79 percent RH (12 percent equilibrium moisture content) to plywood exposed at 50 percent RH (6 percent equilibrium moisture content) shows that the rate of thermally induced strength loss was increased at the higher wood equilibrium moisture content. However, the reader should note that the magnitude of the increased effect resulting from increased equilibrium moisture content (Fig. 7) was not as great as the effect of increased temperature (Figs. 3 to 6).

Our practical experience in running the protocol was that RH above 70 percent at 170°F (77°C) promoted excessive corrosion in the equipment. We also noted that although temperature within an environmental chamber was relatively easy to monitor and control, accurate monitoring and control of RH at the elevated temperatures was more difficult. Thus, the desired RH condition was not as controllable as it should be for a standard test method. These findings, together with the discrepancy in strength results related to RH (Fig. 7), indicate the need for an empirical procedure to account for the effect of different RH. The following procedure uses the relative vapor pressures of water at various RH to adjust data obtained at one temperature and RH condition to another RH condition. This procedure and examples of its use are described in the new ASTM Standard (ASTM 1991). Using this procedure, we can calculate an experimentally derived rate of thermal degrade ($k_1 = d(\text{MOR})/dt$) at the experimental temperature and RH condition through linear regression:

$$\text{MOR} = b_0 + k_1 t \tag{1}$$

where

t is time (days),

b_0 regression constant (at T_1 and RH_1),

k_1 regression slope (at T_1 and RH_1),

T_1 temperature (experimental), and

RH_1 relative humidity (experimental).

We then adjust that experimentally derived rate constant (k_1) to a standard rate of thermal degradation (k_2) at some predefined consensus RH condition:

$$k_2 = k_1(\mathrm{RH}_2/\mathrm{RH}_1) \quad (2)$$

where RH_2 is currently defined as 67 percent RH (ASTM 1991). Using this approach, the effects of temperature on strength at one RH condition were found to reasonably predict the effects on strength at another RH condition.

Specific Gravity

Extended thermal exposure apparently exerts no measurable effect on the specific gravity of untreated or MAP-treated plywood (Table A7). This lack of measurable effect eliminates the possibility of monitoring specific gravity (that is, density) to nondestructively evaluate the possible extent of thermally induced strength loss.

Moisture Content

A definite moisture content hysteresis is apparent in the results shown in Table A7 and Figures 8 and 9. Untreated specimens exposed at 130°F (54°C)-73 percent RH and 170°F (and 77°C)-50 percent RH approached equilibrium under adsorbing conditions and equilibrated at approximately 10 percent moisture content. Untreated specimens exposed at 150°F (65°C)-76 percent RH and 170°F (77°C)-79 percent RH approached equilibrium under desorbing conditions and equilibrated at approximately 12 percent moisture content. The MAP-treated specimens also followed this pattern of hysteresis, but they tended **to** equilibrate at about 1 to 2 percent higher equilibrium moisture content than their untreated counterparts. In the future, this protocol should be run in a way that assures that all specimens approach moisture equilibrium under either all adsorbing or all desorbing conditions. This would facilitate comparison of mechanical property results.

Note that regardless of whether the specimens approached moisture equilibrium under adsorbing or desorbing conditions, the eventual equilibrium moisture content of both treated and untreated specimens tended to be slowly reduced after extended exposure to elevated temperature (Figs. 8, 9). The exceptions were the untreated 130°F and 150°F (54°C and 65°C) exposure groups and the untreated and MAP-treated groups from FPL exposed at 170°F (77°C)-79 percent RH. Note that treated specimens tended to exhibit decreased hygroscopicity more than did untreated specimens. This permanent, reduction in plywood hygroscopicity as witnessed by reduced equilibrium moisture content after extended exposure to elevated temperature is similar in nature and in magnitude to the trend noted earlier in our work with small clear specimens of Southern Pine (LeVan and others 1990). In that report,

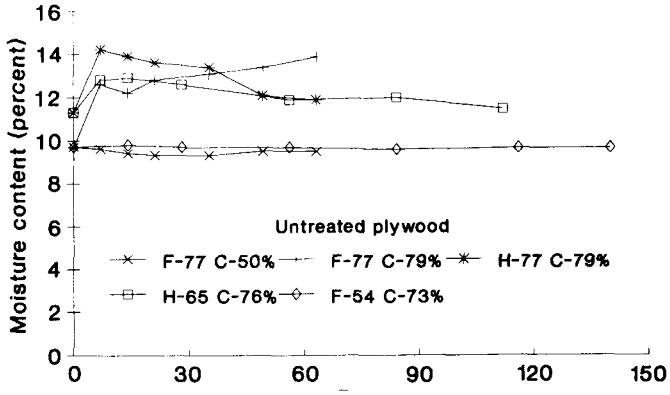

Figure 8—Effect of exposure to various temperatures on equilibrium moisture content of untreated plywood.

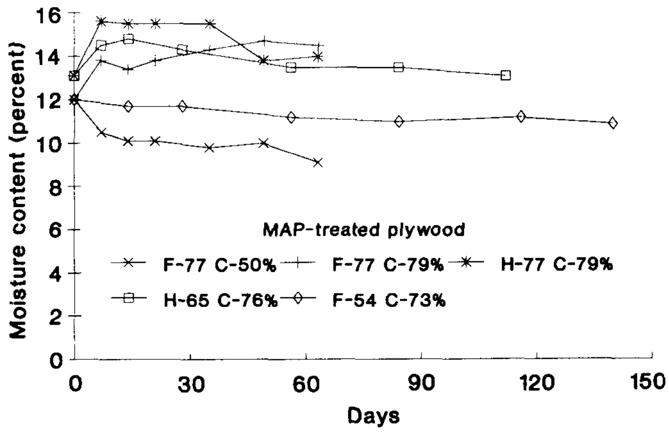

Figure 9—Effect of exposure to various temperatures on equilibrium moisture content of MAP-treated plywood.

we showed that the permanent reduction in equilibrium moisture content resulted from the hydrolysis of certain hemicelluloses that provide secondary bonding sites for bound water.

Mechanical Testing

Extended exposure to elevated temperatures induced similar strength property reductions in bending (Figs. 1, 3, 4) and tensile (Figs. 2, 5, 6) properties. Accordingly, we decided to discontinue the tension tests. In addition, we decided to mandate the calculation and reporting of work to maximum load (WML) because a load that induces a bending stress was considered to be a more likely scenario with plywood roof sheathing than a load that induces a pure tensile stress. Our results confirm that WML is the most seriously affected mechanical property (Tables A8, A9). Three other advantages of reporting WML for roof sheathing panels are as follows:

1. WML may be a legitimate predictor of a panel's ability to deform to accommodate normal irregularities in truss height,[1]
2. changes in WML tend to be of a greater magnitude than changes in MOR and thus WML changes are easier to identify, and
3. changes in WML seem to act as a precursor of future trends in MOR.

Cutting Pattern

The ramifications of treatment gradients were considered during the evolution of the protocol. To eliminate the undesirable influence of a treatment gradient associated with differential chemical absorption along the edges of a treated plywood sheet, all material within 2 in. (50 mm) of the long edges of the original 4- by 8-ft (1.22- by 2.44-m) plywood panels should be eliminated.

Distributional Effects

Wood properties exhibit variability about some average tendency. Thermal exposure could affect both the average and the distributional form of those properties. Thus, although the experiments were primarily designed to address mean effects, the distributional characteristics of the mechanical properties studied were also considered and evaluated.

Mean MOR and MOE values over the duration of exposure were compared to fifth percentile estimates of the MOR and MOE distributions. Distributions were fitted for normal or two-parameter Weibull distributions. Nonparametric fits were also obtained by using a rank-order technique for the 20 specimens. As might be expected when generating lower tail estimates based on sample sizes of 20 specimens, the variability of the fifth percentile estimates for any given mechanical property was great. After careful examination, no single fit or estimation technique could be considered as describing the central tendency (mean) or lower tails any better than any other technique. Most importantly, no apparent differences were discernible between the trends in the lower tails and mean trends. Thus, all further evaluations were based on the more stable estimates of mean.

Increasing the number of specimens in each bending group from 20 to 30 specimens might be beneficial. Although this larger sample size would not greatly increase the accuracy of estimates of mean trends, it would allow investigators to place a 75-percent confidence limit on the nonparametric estimate of the fifth percentile (ASTM 1990a). Specifically, this change would provide an ability to monitor distributional effects on bending properties.

Predictability

Strength loss can be predicted from exposure time at elevated temperature, based on earlier work by Millett and coworkers (Mitchell and others 1953, 1967, 1972). Accordingly, the strength data were evaluated using kinetic theory by deriving an Arrhenius-type relationship to predict thermally induced strength loss. Previous work by Stamm (1964) also supports this approach. All data generated from the protocol suggest a linear relationship between mechanical properties and duration of exposure to elevated temperatures. Prediction of a first-order chemical or thermal effect requires an estimate of the rate of change. For cellulosic materials, this rate constant can represent a. change in concentration of a chemical constituent or a change in a measured property, such as strength (Millett and Gerhards 1972). The rate constant is a function of temperature. Changes in the adjusted standard rate constant k_2 can be related to changes in temperature by an Arrhenius equation:

$$k_2 = Ae^{(-E_a/RT)} \tag{3}$$

where

k_2 is adjusted standard rate constant at 67 percent RH,
A pre-exponential factor,
E_a activation energy,
R gas constant, and
T temperature (K).

When the Arrhenius equation is expressed in terms of natural logrithims,

$$\ln(k_2) = \ln(A) + (-E_a/RT) \tag{4}$$

The activation energy E_a and pre-exponential factor A can then be determined graphically from a plot of the logarithm of adjusted standard rate constant as a function of reciprocal temperature or by linear regression. Once these two parameters are known, the rate constant at other temperatures can be predicted.

[1] Zylkowski, S.C. 1990. Personal communication (December 7, 1990), with Steven C. Zylkowski, Manager, Research and Development, American Plywood Association, Tacoma, WA.

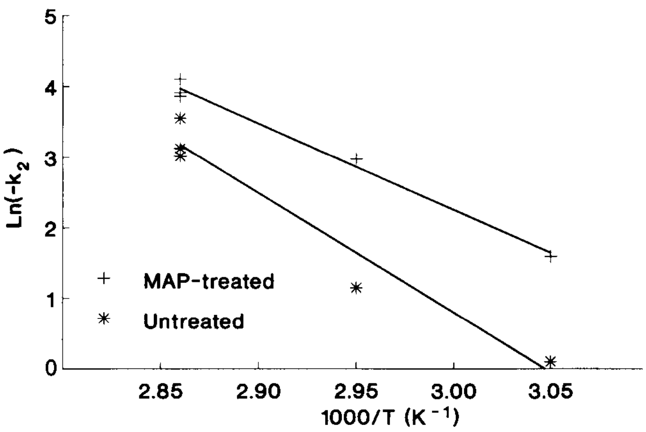

Figure 10—Arrhenius plot of reaction rate (ln(-k_2) versus $1/T$). The value k_2 is the standard rate of thermal degrade derived in Equation (2) at each *temperature (T_K).*

The application of an Arrhenius-kinetic approach to modeling chemical rate constants for wood and wood-based materials is more completely discussed by Millett and Gerhards (1972) and Stamm (1964).

Using the initial data generated at three temperatures in the test protocol, we applied Arrhenius theory to predict the rate constants associated with the change in some mechanical property to other temperatures. Examples of this relationship are shown for MOR in Figure 10. Note that both the untreated and MAP-treated materials could generally be considered as undergoing a linear rate of change. Also note that when using this first-order (linear) analysis, the rates of change between treated and untreated materials are somewhat similar. These results tend to support a linear cumulative damage model. Variations of such models have been theorized (Stamm 1964, Gerhards 1979, Caulfield 1985). These results also substantiate the work of Millett and Gerhards (1972) in that kinetic-based models can successfully predict thermally induced mechanical property degradation for wood materials. Although our current ability to predict thermally induced degradation is elementary, the long-range goal of developing an ability to predict serviceability may be obtainable.

Further Considerations

The processing conditions employed in this study were closely matched to the conditions imposed in commercial treating and redrying schedules. Nevertheless, the magnitude of strength loss in our experiments was less than that of some field experience. This might have been due to the quality of the chemicals used or to processing conditions. Our recent work with small clear specimens of Southern Pine pointed to the importance of chemical formulation and post-treatment redrying in accelerating the subsequent susceptibility of the wood to thermally induced strength loss (LeVan and others 1990).

Based on the unacceptable performance of some FR treatments, FR-treated materials should not be considered interchangeable commodity items. Architects and engineers must be aware of the fact that different FR treatments may behave differently under thermal exposure. An approved third-party inspection agency should certify compliance with all existing standards, processing methods, and testing procedures. Such procedures include compliance with AWPA C20/C27 and ASTM E-84, with chemical formulation and post-treatment drying temperatures employed in developing the original certification, and with performance data from the new ASTM test method (1991) for assessing ongoing thermally induced strength degradation.

Because of the possibility that high moisture contents may interact with FR-treated material exposed to elevated temperatures, AWPA Standards C27 for FR-treated plywood and C20 for FR-treated lumber recognize that all FR-treated material must be dried after treatment to ≤15 percent moisture content for plywood and ≤19 percent moisture content for lumber. These moisture content levels are required for proper structural performance, and especially for avoiding fastener corrosion. Thus, adequate precautions must also be used during shipping and at the job site to prevent moisture from rewetting the FR-treated material. If FR-treated material is exposed to rain, it should be allowed to dry thoroughly before it is covered with roofing material.

Conclusions

Using the new test protocol (ASTM 1991), thermally induced strength losses were evident in laboratory simulations within a reasonably short period. The environmental conditions used in the laboratory activated chemical reactions that affected mechanical properties in a manner similar to that experienced in the field. The results of this test protocol seem to present the engineering community with a reasonable comparative procedure for assessing the potential of commercial FR treatments to cause thermally induced in-service strength loss. Thus, results from this protocol can be used to begin the process of substantiating acceptable field performance for new or existing FR-treatments before they are used in service conditions with periodic or sustained exposure to elevated temperatures.

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Appendix A. Results of Experimental Tests

The tables in the Appendix (Tables A1-A6, A8-A9) show the effects of extended exposure at elevated temperature on mechanical properties of untreated and fire-retardant-treated plywood. Table A7 shows moisture content and specific gravity values of untreated and treated plywood for each exposure combination (treatment-temperature-humidity-exposure duration).

Table A1—Modulus of elasticity and stiffness of untreated material exposed to elevated temperatures

Temperature (°F (°C))	RH (%)	Design[a]	Exposure (days)	Modulus of elasticity ($\times 10^6$ lb/in^2 (GPa)) Mean	Modulus of elasticity Standard deviation	Stiffness ($\times 10^3$ lb·in^2 (N·m^2)) Mean	Stiffness Standard deviation	Sample size
80 (27)	65	Random	0	1.557 (10.74)	0.280 (1.93)	65.66 (188.43)	13.51 (38.77)	19
		Blocked	0	1.381 (9.52)	0.308 (2.12)	67.31 (193.17)	15.32 (43.96)	21
130 (54)	73	Random	14	1.496 (10.31)	0.207 (1.43)	66.31 (190.30)	16.16 (46.38)	20
			28	1.575 (10.86)	0.242 (1.67)	67.46 (193.60)	10.31 (29.59)	20
			56	1.626 (11.21)	0.351 (2.42)	69.82 (200.37)	15.20 (43.62)	19
			84	1.540 (10.62)	0.317 (2.19)	65.98 (189.35)	14.55 (41.76)	20
			116	1.692 (11.67)	0.396 (2.73)	67.08 (192.51)	15.88 (45.57)	20
			140	1.781 (12.28)	0.268 (1.85)	69.58 (199.68)	12.25 (35.16)	20
150 (65)	76	Blocked	7	1.401 (9.66)	0.220 (1.52)	63.73 (182.89)	10.85 (31.14)	21
			14	1.243 (8.57)	0.263 (1.81)	56.72 (162.78)	13.40 (38.46)	21
			28	1.270 (8.76)	0.292 (2.01)	59.02 (169.38)	13.89 (39.86)	20
			56	1.340 (9.24)	0.239 (1.65)	59.18 (169.84)	9.36 (26.86)	21
			84	1.298 (8.95)	0.269 (1.85)	58.88 (168.97)	13.36 (38.34)	21
			112	1.396 (9.63)	0.276 (1.90)	63.06 (180.97)	11.78 (33.81)	21
170 (77)	79	Random	7	1.449 (9.99)	0.286 (1.97)	65.10 (186.82)	12.87 (36.93)	20
			14	1.515 (10.45)	0.261 (1.80)	65.74 (188.66)	12.05 (34.58)	20
			21	1.516 (10.45)	0.311 (2.14)	66.85 (191.85)	13.34 (38.28)	19
			35	1.458 (10.05)	0.154 (1.06)	64.82 (186.02)	7.34 (21.06)	20
			49	1.280 (8.83)	0.242 (1.67)	59.47 (170.67)	11.34 (32.54)	20
			63	1.268 (8.74)	0.281 (1.94)	58.95 (169.18)	13.50 (38.74)	20
170 (77)	79	Blocked	7	1.353 (9.33)	0.434 (2.99)	62.21 (178.53)	18.00 (51.66)	21
			14	1.322 (9.12)	0.217 (1.50)	62.04 (178.04)	10.61 (30.45)	21
			21	1.234 (8.51)	0.227 (1.57)	60.82 (174.54)	11.08 (31.80)	21
			35	1.206 (8.32)	0.287 (1.98)	57.31 (164.47)	13.37 (38.37)	21
			49	1.282 (8.84)	0.242 (1.67)	58.99 (169.29)	10.64 (30.53)	21
			63	1.380 (9.52)	0.279 (1.92)	62.38 (179.02)	12.93 (37.11)	21
170 (77)	50	Random	7	1.558 (10.74)	0.301 (2.08)	65.08 (186.77)	12.01 (34.47)	20
			14	1.662 (11.46)	0.265 (1.83)	64.94 (186.36)	11.08 (31.80)	20
			21	1.583 (10.91)	0.217 (1.50)	66.83 (191.79)	10.06 (28.87)	20
			35	1.502 (10.36)	0.317 (2.19)	62.55 (179.51)	13.09 (37.56)	20
			49	1.430 (9.86)	0.348 (2.40)	58.01 (166.48)	13.30 (38.17)	20
			63	1.625 (11.20)	0.314 (2.17)	67.89 (194.83)	12.98 (37.25)	20

[a] Specimens allotted to blocked design were tested by Hickson Corporation.
All other specimens were allotted to random design and tested at the FPL

Table AP—Modulus of elasticity and stiffness of treated material exposed to elevated temperatures

Temper-ature (°F (°C))	RH (%)	Design[a]	Exposure (days)	Modulus of elasticity ($\times 10^6$ lb/in^2 (GPa))		Stiffness ($\times 10^3$ lb·in^2 (N·m^2))		Sample size
				Mean	Standard deviation	Mean	Standard deviation	
80 (27)	65	Random	0	1.468 (10.12)	0.268 (1.85)	67.53 (193.80)	12.09 (34.70)	19
		Blocked	0	1.208 (8.33)	0.271 (1.87)	63.01 (180.83)	15.20 (43.62)	21
130 (54)	73	Random	14	1.348 (9.29)	0.229 (1.58)	62.93 (180.60)	10.55 (30.28)	20
			28	1.382 (9.53)	0.256 (1.77)	64.46 (184.99)	11.41 (32.74)	20
			56	1.498 (10.33)	0.272 (1.88)	71.71 (205.79)	12.25 (35.16)	20
			84	1.560 (10.76)	0.192 (1.32)	74.06 (212.54)	9.29 (26.66)	20
			116	1.698 (11.71)	0.247 (1.70)	76.02 (218.16)	10.87 (31.19)	19
			140	1.617 (11.15)	0.336 (2.32)	69.80 (200.31)	14.05 (40.32)	20
150 (65)	76	Blocked	7	1.152 (7.94)	0.212 (1.46)	56.82 (163.06)	10.17 (29.19)	21
			14	1.204 (8.30)	0.231 (1.59)	60.19 (172.73)	11.57 (33.20)	21
			28	1.266 (8.73)	0.264 (1.82)	61.47 (176.41)	13.39 (38.43)	21
			56	1.236 (8.52)	0.228 (1.57)	59.48 (170.70)	11.00 (31.57)	21
			84	1.222 (8.43)	0.232 (1.60)	60.15 (172.62)	12.45 (35.73)	21
			112	1.231 (8.49)	0.253 (1.74)	60.14 (172.59)	13.24 (38.00)	21
170 (77)	79	Random	7	1.326 (9.14)	0.258 (1.78)	63.19 (181.34)	11.98 (34.38)	19
			14	1.258 (8.67)	0.229 (1.58)	58.13 (166.82)	9.86 (28.30)	20
			21	1.321 (9.11)	0.238 (1.64)	62.90 (180.51)	11.23 (32.23)	20
			35	1.307 (9.01)	0.265 (1.83)	62.50 (179.36)	13.16 (37.77)	20
			49	1.247 (8.60)	0.224 (1.54)	58.91 (169.06)	10.71 (30.74)	20
			63	1.315 (9.07)	0.255 (1.76)	62.58 (179.59)	12.10 (34.72)	20
170 (77)	79	Blocked	7	1.242 (8.56)	0.244 (1.68)	62.80 (180.22)	11.93 (34.24)	21
			14	1.317 (9.08)	0.203 (1.40)	65.40 (187.68)	9.07 (26.03)	21
			21	1.273 (8.78)	0.263 (1.81)	65.16 (187.00)	13.99 (40.15)	21
			35	1.126 (7.76)	0.249 (1.72)	56.52 (162.20)	11.60 (33.29)	21
			49	1.195 (8.24)	0.274 (1.89)	59.49 (170.72)	14.98 (42.99)	21
			63	1.192 (8.22)	0.227 (1.57)	56.58 (162.37)	11.54 (33.12)	21
170 (77)	50	Random	7	1.436 (9.90)	0.338 (2.33)	65.24 (187.23)	16.08 (46.15)	20
			14	1.456 (10.04)	0.302 (2.08)	63.89 (183.35)	13.98 (40.12)	20
			21	1.464 (10.09)	0.275 (1.90)	66.27 (190.18)	12.87 (36.93)	20
			35	1.472 (10.15)	0.254 (1.75)	66.33 (190.35)	12.29 (35.27)	20
			49	1.489 (10.27)	0.367 (2.53)	66.26 (190.15)	15.82 (45.40)	20
			63	1.546 (10.66)	0.236 (1.63)	70.72 (202.95)	11.99 (34.41)	20

[a] Specimens allotted to blocked design were tested by Hickson Corporation.
All other specimens were allotted to random design and tested at the FPL.

Table A3—Modulus of rupture and maximum bending moment of untreated material exposed to elevated temperatures

Temperature (°F (°C))	RH (%)	Design[a]	Exposure (days)	Modulus of rupture ($\times 10^3$ lb/in^2 (MPa)) Mean	Modulus of rupture Standard deviation	Maximum bending moment ($\times 10^3$ lb·in (N·m)) Mean	Maximum bending moment Standard deviation
80 (27)	65	Random	0	10.81 (74.5)	2.14 (14.8)	1.65 (186.4)	0.34 (38.4)
		Blocked	0	8.50 (58.6)	1.30 (9.0)	1.42 (160.4)	0.20 (22.6)
130 (54)	73	Random	14	10.35 (71.4)	1.34 (9.2)	1.58 (178.5)	0.20 (22.6)
			28	10.39 (71.6)	1.94 (13.4)	1.60 (180.8)	0.30 (33.9)
			56	9.88 (68.1)	1.81 (12.5)	1.53 (172.9)	0.28 (31.6)
			84	9.75 (67.2)	1.63 (11.2)	1.51 (170.6)	0.27 (30.5)
			116	10.47 (72.2)	2.21 (15.2)	1.53 (172.9)	0.32 (36.2)
			140	10.52 (72.5)	1.58 (10.9)	1.53 (172.9)	0.26 (29.4)
150 (65)	76	Blocked	7	9.52 (65.6)	1.20 (8.3)	1.53 (172.9)	0.23 (26.0)
			14	9.32 (64.3)	1.74 (12.0)	1.50 (169.5)	0.31 (35.0)
			28	9.08 (62.6)	1.49 (10.3)	1.48 (167.2)	0.24 (27.1)
			56	9.66 (66.6)	1.66 (11.4)	1.52 (171.7)	0.25 (28.2)
			84	8.86 (61.1)	1.53 (10.5)	1.42 (160.4)	0.26 (29.4)
			112	9.64 (66.5)	1.66 (11.4)	1.54 (174.0)	0.26 (29.4)
170 (77)	79	Random	7	9.40 (64.8)	1.74 (12.0)	1.50 (169.5)	0.27 (30.5)
			14	9.86 (68.0)	1.46 (10.1)	1.53 (172.9)	0.23 (26.0)
			21	9.06 (62.5)	1.45 (10.0)	1.43 (161.6)	0.22 (24.9)
			35	8.81 (60.7)	1.14 (7.9)	1.40 (158.2)	0.20 (22.6)
			49	7.86 (54.2)	1.12 (7.7)	1.28 (144.6)	0.19 (21.5)
			63	7.45 (51.4)	1.11 (7.7)	1.21 (136.7)	0.17 (19.2)
170 (77)	79	Blocked	7	8.22 (56.7)	1.58 (10.9)	1.34 (151.4)	0.28 (31.6)
			14	8.10 (55.8)	1.68 (11.6)	1.33 (150.3)	0.29 (32.8)
			21	7.71 (53.2)	1.35 (9.3)	1.31 (148.0)	0.23 (26.0)
			35	7.69 (53.0)	1.80 (12.4)	1.27 (143.5)	0.30 (33.9)
			49	8.24 (56.8)	1.35 (9.3)	1.34 (151.4)	0.21 (23.7)
			63	8.98 (61.9)	1.70 (11.7)	1.44 (162.7)	0.29 (32.8)
170 (77)	50	Random	7	10.19 (70.3)	2.19 (15.1)	1.55 (175.1)	0.32 (36.2)
			14	10.69 (73.7)	1.81 (12.5)	1.55 (175.1)	0.27 (30.5)
			21	10.14 (69.9)	12.8 (8.8)	1.55 (175.1)	0.20 (22.6)
			35	10.22 (70.5)	1.83 (12.6)	1.55 (175.1)	0.27 (30.5)
			49	9.10 (62.7)	2.31 (15.9)	1.36 (153.7)	0.34 (38.4)
			63	9.98 (68.8)	2.13 (14.7)	1.51 (170.6)	0.32 (36.2)

[a] Specimens allotted to blocked design were tested by Hickson Corporation.
All other specimens were allotted to random design and tested at the FPL.
Sample size was the same as that for experiments on MOE and stiffness (see Table Al).

Table A4—Modulus of rupture and maximum bending moment of treated material exposed to elevated temperatures

Temperature (°F (°C))	RH (%)	Design[a]	Exposure (days)	Modulus of rupture ($\times 10^3$ lb/in^2 (MPa)) Mean	Modulus of rupture Standard deviation	Maximum bending moment (lb·in (N·m)) Mean	Maximum bending moment Standard deviation
80 (27)	65	Random	0	8.68 (59.8)	1.65 (11.4)	1.41 (159.3)	0.26 (29.4)
		Blocked	0	7.14 (49.2)	1.09 (7.5)	1.25 (141.2)	0.20 (22.6)
130 (54)	73	Random	14	8.32 (57.4)	1.45 (10.0)	1.36 (153.7)	0.24 (27.1)
			28	7.99 (55.1)	1.29 (8.9)	1.31 (148.0)	0.21 (23.7)
			56	8.33 (57.4)	1.32 (9.1)	1.39 (157.1)	0.21 (23.7)
			84	7.64 (52.7)	1.23 (8.5)	1.27 (143.5)	0.21 (23.7)
			116	7.94 (54.7)	1.37 (9.4)	1.27 (143.5)	0.24 (27.1)
			140	7.73 (53.3)	1.81 (12.5)	1.20 (135.6)	0.29 (32.8)
150 (65)	76	Blocked	7	7.48 (51.6)	0.90 (6.2)	1.27 (143.5)	0.15 (16.9)
			14	7.29 (50.3)	1.04 (7.2)	1.25 (141.2)	0.18 (20.3)
			28	7.28 (50.2)	1.48 (10.2)	1.22 (137.8)	0.25 (28.2)
			56	6.10 (42.1)	1.13 (7.8)	1.02 (115.2)	0.19 (21.5)
			84	5.69 (39.2)	1.08 (7.4)	0.96 (108.5)	0.19 (21.5)
			112	4.94 (34.1)	1.10 (7.6)	0.83 (93.8)	0.20 (22.6)
170 (77)	79	Random	7	6.79 (46.8)	1.36 (9.4)	1.13 (127.7)	0.24 (27.1)
			14	5.78 (39.9)	1.04 (7.2)	0.94 (106.2)	0.16 (18.1)
			21	5.91 (40.7)	1.54 (10.6)	0.98 (110.7)	0.25 (28.2)
			35	5.48 (37.8)	1.36 (9.4)	0.91 (102.8)	0.23 (26.0)
			49	4.23 (29.2)	0.92 (6.3)	0.70 (79.1)	0.15 (16.9)
			63	4.54 (31.3)	1.12 (7.7)	0.75 (84.7)	0.19 (21.5)
170 (77)	79	Blocked	7	6.60 (45.5)	0.86 (5.9)	1.14 (128.8)	0.14 (15.8)
			14	5.90 (40.7)	1.37 (9.4)	1.00 (113.0)	0.22 (24.9)
			21	5.43 (37.4)	1.13 (7.8)	0.94 (106.2)	0.20 (22.6)
			35	4.46 (30.8)	0.76 (5.2)	0.77 (87.0)	0.13 (14.7)
			49	3.92 (27.0)	1.29 (8.9)	0.66 (74.6)	0.22 (24.9)
			63	3.50 (24.1)	0.99 (6.8)	0.58 (65.5)	0.16 (18.1)
170 (77)	50	Random	7	8.06 (55.6)	1.43 (9.9)	1.29 (145.8)	0.24 (27.1)
			14	6.57 (45.3)	1.54 (10.6)	1.03 (116.4)	0.25 (28.2)
			21	6.20 (42.7)	1.37 (9.4)	0.99 (111.9)	0.20 (22.6)
			35	6.04 (41.6)	1.17 (8.1)	0.97 (109.6)	0.20 (22.6)
			49	5.85 (40.3)	1.74 (12.0)	0.93 (105.1)	0.27 (30.5)
			63	5.45 (37.6)	1.21 (8.3)	0.87 (98.3)	0.18 (20.3)

[a]Specimens allotted to blocked design were tested by Hickson Corporation. All other specimens were allotted to random design and tested at the FPL. Sample size was the same as that for experiments on MOE and stiffness (see Table A2).

Table A5—Ultimate tensile stress of untreated material exposed to elevated temperatures

Temperature (°F(°C))	RH (%)	Design[a]	Exposure (days)	Ultimate tensile stress ($\times 10^3$ lb/in^2 (MPa)) Mean	Standard deviation	Sample size
80 (27)	65	Random	0	6.67 (46.0)	1.41 (9.7)	20
		Blocked	0	5.69 (39.2)	1.04 (7.2)	20
130 (54)	73	Random	14	5.66 (39.0)	1.49 (10.3)	20
			28	5.76 (39.7)	1.06 (7.3)	20
			56	5.80 (40.0)	1.37 (9.4)	20
			84	6.51 (44.9)	1.19 (8.2)	20
			116	5.93 (40.9)	1.03 (7.1)	20
			140	6.13 (42.3)	1.96 (13.5)	20
150 (65)	76	Blocked	7	5.46 (37.6)	1.15 (7.9)	20
			14	6.12 (42.2)	1.24 (8.5)	20
			28	5.61 (38.7)	1.14 (7.9)	20
			56	5.67 (39.1)	1.03 (7.1)	20
			84	5.70 (39.3)	1.12 (7.7)	20
			112	5.67 (39.1)	1.03 (7.1)	20
170 (77)	79	Random	7	5.78 (39.9)	1.17 (8.1)	20
			14	5.96 (41.1)	1.20 (8.3)	20
			21	5.83 (40.2)	1.85 (12.8)	20
			35	5.52 (38.1)	1.25 (8.6)	20
			49	5.63 (38.8)	1.23 (8.5)	20
			63	4.88 (33.6)	0.84 (5.8)	20
170 (77)	79	Blocked	7	5.31 (36.6)	1.01 (7.0)	20
			14	5.39 (37.2)	1.29 (8.9)	20
			21	5.13 (35.4)	0.98 (6.8)	20
			35	4.90 (33.8)	1.20 (8.3)	20
			49	5.15 (35.5)	1.07 (7.4)	20
			63	4.80 (33.1)	1.36 (9.4)	20

[a]Specimens allotted to blocked design were tested by Hickson Corporation. All other specimens were allotted to random design and tested at the FPL.

Table A6—Ultimate tensile stress of treated material exposed to elevated temperatures

Temperature (°F(°C))	RH (%)	Design[a]	Exposure (days)	Ultimate tensile stress ($\times 10^3$ lb/in^2 (MPa))		Sample size
				Mean	Standard deviation	
80 (27)	65	Random	0	4.85 (33.4)	0.74 (5.1)	20
		Blocked	0	5.13 (35.4)	1.39 (9.6)	20
130 (54)	73	Random	14	5.39 (37.2)	0.89 (6.1)	20
			28	4.85 (33.4)	0.90 (6.2)	20
			56	4.82 (33.2)	0.80 (5.5)	20
			84	4.35 (30.0)	1.09 (7.5)	20
			116	4.32 (29.8)	1.01 (7.0)	20
			140	4.15 (28.6)	0.63 (4.3)	20
150 (65)	76	Blocked	7	4.35 (30.0)	1.04 (7.2)	20
			14	4.67 (32.2)	0.97 (6.7)	20
			28	4.24 (29.2)	1.20 (8.3)	20
			56	3.36 (23.2)	0.96 (6.6)	20
			84	2.83 (19.5)	0.55 (3.8)	20
			112	2.74 (18.9)	0.63 (4.3)	20
170 (77)	79	Random	7	3.77 (26.0)	0.95 (6.6)	18
			14	3.60 (24.8)	0.63 (4.3)	20
			21	2.90 (20.0)	0.66 (4.6)	20
			35	2.32 (16.0)	0.55 (3.8)	20
			49	2.01 (13.9)	0.47 (3.2)	19
			63	1.89 (13.0)	0.38 (2.6)	20
170 (77)	79	Blocked	7	4.54 (31.3)	1.10 (7.6)	20
			14	3.81 (26.3)	0.68 (4.7)	20
			21	2.82 (19.4)	0.87 (6.0)	20
			35	2.09 (14.4)	0.55 (3.8)	20
			49	1.94 (13.4)	0.54 (3.7)	20
			63	1.45 (10.0)	0.48 (3.3)	20

[a] Specimens allotted to blocked design were tested by Hickson Corporation. All other specimens were allotted to random design and tested at the FPL.

Table A7—Moisture content and specific gravity of plywood exposed to elevated temperatures

Group[a]	Temperature (°F (°C))	RH (%)	Time (days)	Moisture content (%) Mean	Moisture content (%) Standard deviation	Specific gravity Mean	Specific gravity Standard deviation	Test site[b]
Control								
Untreated	80 (27)	65	0	9.7	0.5	0.55	0.03	F
				11.3	0.9	0.58	0.04	H
Treated	80 (27)	65	0	12.0	0.2	0.57	0.02	F
				13.1	0.2	0.60	0.02	H
Untreated	130 (54)	73	14	9.8	0.3	0.52	0.02	F
			28	9.7	0.3	0.55	0.02	F
			56	9.7	0.2	0.54	0.03	F
			84	9.6	0.3	0.54	0.03	F
			116	9.7	0.2	0.54	0.02	F
			140	9.7	0.2	0.54	0.03	F
Treated	130 (54)	73	14	11.7	0.4	0.55	0.03	F
			28	11.7	0.1	0.56	0.03	F
			56	11.2	0.1	0.57	0.02	F
			84	11.0	0.2	0.57	0.02	F
			116	11.2	0.1	0.58	0.03	F
			140	10.9	0.1	0.57	0.03	F
Untreated	150 (65)	75	7	12.8	0.4	0.57	0.03	H
			14	12.9	0.3	0.56	0.03	H
			28	12.6	0.6	0.55	0.03	H
			56	11.9	0.3	0.57	0.03	H
			84	12.0	0.4	0.55	0.03	H
			112	11.5	0.4	0.57	0.03	H
Treated	150 (65)	75	7	14.5	0.4	0.59	0.02	H
			14	14.8	0.4	0.58	0.02	H
			28	14.3	0.3	0.59	0.02	H
			56	13.5	0.6	0.58	0.03	H
			84	13.5	0.3	0.57	0.02	H
			112	13.1	0.5	0.56	0.03	H
Untreated	170 (77)	79	7	12.6	0.2	0.55	0.03	F
			14	12.2	0.3	0.54	0.02	F
			21	12.8	0.3	0.53	0.03	F
			35	13.1	0.5	0.53	0.03	F
			49	13.4	0.3	0.54	0.03	F
			63	13.9	0.3	0.51	0.02	F

Table A7—Moisture content and specific gravity of plywood exposed to elevated temperatures-concluded

Group[a]	Temper-ature (°F (°C))	RH (%)	Time (days)	Moisture content (%) Mean	Moisture content (%) Standard deviation	Specific gravaity Mean	Specific gravaity Standard deviation	Test site[b]
Treated	170 (77)	79	7	13.8	0.3	0.56	0.04	F
			14	13.4	0.3	0.56	0.02	F
			21	13.8	0.3	0.56	0.02	F
			35	14.3	0.2	0.55	0.03	F
			49	14.7	0.3	0.54	0.03	F
			63	14.5	0.3	0.54	0.03	F
Untreated	170 (77)	79	7	14.2	1.1	0.56	0.02	H
			14	13.9	0.4	0.55	0.02	H
			21	13.6	0.5	0.54	0.03	H
			35	13.4	0.4	0.54	0.02	H
			49	12.1	0.2	0.55	0.03	H
			63	11.9	0.5	0.56	0.03	H
Treated	170 (77)	79	7	15.6	0.3	0.57	0.03	H
			14	15.5	0.5	0.58	0.03	H
			21	15.5	0.9	0.57	0.03	H
			35	15.5	0.6	0.56	0.03	H
			49	13.8	0.4	0.57	0.03	H
			63	14.0	1.0	0.56	0.03	H
Untreated	170 (77)	50	7	9.6	0.3	0.53	0.03	F
			14	9.4	0.2	0.53	0.03	F
			21	9.3	0.2	0.56	0.02	F
			35	9.3	0.2	0.55	0.02	F
			49	9.5	0.2	0.54	0.03	F
			63	9.5	0.1	0.58	0.03	F
Treated	170 (77)	50	7	10.5	0.2	0.58	0.03	F
			14	10.1	0.2	0.57	0.02	F
			21	10.1	0.3	0.58	0.03	F
			35	9.8	0.2	0.59	0.03	F
			49	10.0	0.2	0.58	0.03	F
			63	9.1	0.2	0.55	0.03	F

[a] Treated with monoammonium phosphate, 3.5 lb/ft^3 (56 kg/m^3).
[b] Specimens allotted to blocked design were tested by Hickson Corporation (H). All other specimens were allotted to random design and tested at the FPL (F)

Table A8—Work to maximum load of untreated material exposed to elevated temperatures

Temperature (°F(°C))	RH (%)	Design[a]	Exposure (days)	Work to maximum load (in·lb/in^3 (kJ/m^3)) Mean	Standard deviation
80 (27)	65	Random	0	6.66 (45.9)	2.90 (20.0)
		Blocked	0	—	—
130(54)	73	Random	14	6.91 (47.6)	1.93 (13.3)
			28	5.97 (41.2)	2.58 (17.8)
			56	5.07 (35.0)	2.23 (15.4)
			84	6.20 (42.7)	2.32 (16.0)
			116	4.26 (29.4)	2.03 (14.0)
			140	4.56 (31.4)	1.20 (8.3)
150 (65)	76	Blocked	7	—	—
			14	—	—
			28	—	—
			56	—	—
			84	—	—
			112	—	—
170 (77)	79	Random	7	6.43 (44.3)	2.59 (17.9)
			14	5.96 (41.1)	1.85 (12.8)
			21	5.30 (36.5)	2.01 (13.9)
			35	5.13 (35.4)	1.79 (12.3)
			49	5.53 (38.1)	2.17 (15.0)
			63	4.71 (32.5)	1.72 (11.9)
170 (77)	79	Blocked	7	—	—
			14	—	—
			21	—	—
			35	—	—
			49	—	—
			63	—	—
170 (77)	50	Random	7	6.50 (44.8)	3.17 (21.9)
			14	6.58 (45.4)	2.65 (18.3)
			21	5.51 (38.0)	2.18 (15.0)
			35	5.80 (40.0)	2.00 (13.8)
			49	5.03 (34.7)	2.71 (18.7)
			63	5.48 (37.8)	3.24 (22.3)

[a] Specimens allotted to blocked design were tested by Hickson Corporation.
All other specimens were allotted to random design and tested at the FPL.

Table A9—Work to maximum load of treated material exposed to elevated temperatures

Temperature (°F(°C))	RH (%)	Design[a]	Exposure (days)	Work to maximum load (in·lb/in^3 (kJ/m^3)) Mean	Standard deviation
80(27)	65	Random	0	4.66 (32.1)	1.61 (11.1)
		Blocked	0	—	—
130 (54)	73	Random	14	4.99 (34.4)	2.32 (16.0)
			28	4.27 (29.4)	1.75 (12.1)
			56	3.83 (26.4)	1.49 (10.3)
			84	3.37 (23.2)	1.51 (10.4)
			116	3.09 (21.3)	1.55 (10.7)
			140	2.89 (19.9)	1.44 (9.9)
150 (65)	76	Blocked	7	—	—
			14	—	—
			28	—	—
			56	—	—
			84	—	—
			112	—	—
170 (77)	79	Random	7	3.33 (23.0)	1.74 (12.0)
			14	2.17 (15.0)	1.30 (9.0)
			21	2.06 (14.2)	1.11 (7.7)
			35	1.75 (12.1)	0.72 (5.0)
			49	1.05 (7.2)	0.49 (3.4)
			63	1.26 (8.7)	0.68 (4.7)
170 (77)	79	Blocked	7	—	—
			14	—	—
			21	—	—
			35	—	—
			49	—	—
			63	—	—
170 (77)	50	Random	7	3.40 (23.4)	1.37 (9.4)
			14	2.42 (16.7)	1.35 (9.3)
			21	1.81 (12.5)	0.68 (4.7)
			35	1.65 (11.4)	0.61 (4.2)
			49	1.62 (11.2)	0.87 (6.0)
			63	1.37 (9.4)	0.66 (4.6)

[a] Specimens allotted to blocked design were tested by Hickson Corporation.
All other specimens were allotted to random design and tested at the FPL.

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