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Durability of Structural Lumber Products After Exposure at 82°C and 80% Relative Humidity

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Abstract

Solid-sawn lumber (Douglas-fir, southern pine, Spruce–Pine–Fir, and yellow-poplar), laminated veneer lumber (Douglas-fir, southern pine, and yellow-poplar), and laminated strand lumber (aspen and yellow-poplar) were heated continuously at 82°C (180°F) and 80% relative humidity (RH) for periods of up to 24 months. The lumber was then reconditioned to room temperature at 20% RH and tested in edgewise bending. Little reduction occurred in modulus of elasticity (MOE) of solid-sawn lumber, but MOE of composite lumber products was somewhat reduced. Modulus of rupture (MOR) of solid-sawn lumber was reduced by up to 50% after 24 months exposure. Reductions in MOR of up to 61% were found for laminated veneer lumber and laminated strand lumber after 12 months exposure. A limited scope study indicated that the results for laminated veneer lumber in edgewise bending are also applicable to flatwise bending. Comparison with previous results at 82°C (180°F)/25% RH and at 66°C (150°F)/20% RH indicate that differences in the permanent effect of temperature on MOR between species of solid-sawn lumber and between solid-sawn lumber and composite lumber products are greater at high humidity levels than at low humidity levels. This report also describes the experimental design of a program to evaluate the permanent effect of temperature on flexural properties of structural lumber, with reference to previous publications on the immediate effect of temperature and the effect of moisture content on lumber properties.

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Keywords: Lumber, laminated veneer lumber, laminated strand lumber, modulus of rupture, modulus of elasticity, long-term temperature exposure

Cover: Former Forest Products Laboratory employees Roy H. Traver (deceased) and John Hillis (retired).

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Background

Temperature has both reversible and permanent effects on the properties of lumber. The National Design Specification (NDS) provides factors (C_t) for adjusting allowable properties for the immediate effect of temperature, but provides little guidance on the permanent effects of heating. Anecdotal information suggests that current design recommendations are inadequate.

Objectives

The primary objective of this paper is to evaluate the effect of prolonged heating in air (permanent effect) on the flexural properties of solid-sawn and composite lumber products exposed at 82°C (180°F) and 80% relative humidity (RH). This paper also documents the scope of the overall research program on the permanent effects of temperature on the flexural properties of structural lumber.

Procedures

Solid-sawn lumber, laminated veneer lumber (LVL), and laminated strand lumber (LSL) were heated continuously for up to 24 months at 82°C (180°F) and 80% RH. After each exposure period, the lumber was conditioned to room temperature at the specified RH and then tested on edge in third-point bending. Solid-sawn lumber species were Douglas-fir, southern pine, Spruce–Pine–Fir, and yellow-poplar. The LVL species were Douglas-fir, southern pine, and yellow-poplar; the LSL species were aspen and yellow-poplar. Two studies of limited scope were also conducted: (1) flatwise as compared with edgewise modulus of rupture (MOR) of Douglas-fir LVL and (2) exposure of small aspen LSL specimens, 43 by 43 mm (1.7 by 1.7 in.) in cross section, as compared with full-size specimens.

Results

As expected, solid-sawn lumber showed little change in modulus of elasticity (MOE) for exposures of up to 24 months. After 12 months exposure, the residual MOE of LVL ranged from 0.70 to 0.89 and that of LSL was about 0.90. (Residual MOE is the ratio of MOE after exposure to MOE of the unexposed control.) After 12 months exposure, the residual MOR of solid-sawn Spruce–Pine–Fir, Douglas-fir, and yellow-poplar was about 0.64 (36% loss) and after 24 months, about 0.60. The results for southern pine were more variable; after 12 months exposure, the residual MOR of one solid-sawn sample was 0.63 and that of another sample was 0.48. The residual MOR of LVL ranged from 0.39 to 0.56 and that of LSL from 0.39 to 0.48. In flatwise tests, the residual MOR of Douglas-fir LVL, which was based on only 6 pieces, was 0.63 after 12 months exposure. This value is consistent with the value of 0.57 for LVL tested edgewise. The small aspen LSL specimens had virtually the same residual MOR after 12 months exposure (0.42) as that of standard 2 by 4 specimens (0.39).

Conclusions

Because MOE is little affected by thermal degradation, it is not a good indicator of the strength of thermally degraded solid-sawn or composite lumber products. Solid-sawn Douglas-fir and Spruce–Pine–Fir are significantly reduced in strength when exposed over long periods to a combination of high temperature and high humidity. There is an indication that solid-sawn southern pine may be more sensitive to thermal degradation than are Douglas-fir and Spruce–Pine–Fir, but the results to date are not consistent. The remaining studies in this ongoing research program promise to help settle this concern. When heated in air, solid-sawn yellow-poplar is no more sensitive to thermal degradation than are Douglas-fir and Spruce–Pine–Fir. A reanalysis of data in the literature indicates that when heated in water, hardwoods are more sensitive to thermal degradation than are softwoods. The difference in the behavior of hardwood when heated in water compared with air appears to be related to the number of acetyl groups in hardwood, which produces more acetic acid when heated in water but not when heated in air. Composite lumber products are more sensitive to thermal degradation than are solid-sawn Douglas-fir and Spruce–Pine–Fir when exposed at higher humidity levels. Our initial studies indicate that the residual MOR of LVL tested in edgewise bending may be used to estimate the residual MOR in flatwise bending.

Durability of Structural Lumber Products After Exposure at 82°C and 80% Relative Humidity

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Introduction

In general, mechanical properties decrease when wood is heated and increase when it is cooled. Up to about 100°C (212°F), at constant moisture content, the relationship between temperature and property is linear and seems reversible. Thus, this "reversible" effect (also called immediate effect) of temperature implies that the property will essentially return to the value at the original temperature if the temperature change is rapid. This effect is the result of a transitory change in the internal energy level of the wood. In addition to this reversible effect, there may also be a permanent, or irreversible, effect when wood is heated for extended periods. This permanent effect results from the degradation of one or more chemical constituents of the cell wall: hemicellulose, cellulose, or lignin (Fengel and Wegener 1984). The extent of the property loss depends on the stress mode, temperature, duration of exposure, moisture content, heating medium, and species of wood (FPL 1999).

Scientists at the Forest Products Laboratory (FPL) have long been interested in the permanent effects of temperature on the mechanical properties of wood. Pioneering research on this subject includes the studies of Koehler and Pillow (1925), Pillow (1929), Stamm (1964), MacLean (1951, 1954, 1955), and Millet and Gerhards (1972). Portions of this research applicable to solid-sawn wood heated in air are discussed in Green and Evans (2003). Two contemporary series of studies are providing complementary information on the permanent effects of temperature on the properties of wood products. One series primarily focuses on the effects of temperature on the flexural properties of southern pine plywood treated with fire-retardant chemicals (LeVan and others 1990, Winandy 2001) but also contains information on permanent temperature effects for untreated southern pine plywood and small clear specimens of solid-sawn southern pine. Much of this research is summarized in Winandy and Rowell (2005). Kinetics-based models for predicting strength loss as a function of exposure temperature and duration of exposure were developed for predicting thermal degradation at various temperatures (Lebow and Winandy 1999). A second series of studies, which includes the results presented in this paper, focuses on the permanent effects of temperature on the properties of untreated solid-sawn and composite 2 by 4 lumber heated in air. (Note: 2 by 4 refers to nominal 2- by 4-in., actual 1.5- by 3.5-in., standard 38- by 89-mm lumber.)

The results of the second series of studies for exposures at 66°C (150°F) and 75% relative humidity (RH) and at 82°C (180°F) and 30% RH were published in Green and others (2003). In the work reported here, we focus on results at 82°C (180°F) and 80% RH. Results for other exposure conditions will be published as they become available. The experimental design of the overall program is also presented. An eventual goal of the second series of studies is the development of analytical models for predicting strength loss as a function of exposure condition.

Overall Research Program

Temperature and moisture content interact with each other as they affect the properties of wood. It is necessary to understand these interactions to predict the effect of exposing wood to high ambient temperatures for long periods. For example, generally speaking, the higher the wood moisture content the greater the effect of temperature on wood properties. This interaction is true for both the immediate and permanent effects of temperature. The length of time wood is exposed to an elevated temperature is also a factor—the longer the exposure the greater the degradation. It has long been assumed that the total effect of temperature on lumber properties can be estimated by combining the change in property resulting from the immediate effect of temperature and the permanent change in properties resulting from elevated temperature exposure. The validity of this assumption has recently been demonstrated for both solid-sawn lumber and structural lumber products (Green and others 2003).

Immediate Effect of Temperature

Over the last 25 years, a series of studies has been conducted to determine the effects of moisture content and temperature on the properties of solid-sawn and composite lumber products. Green and Evans (1989, 2001b) and Green (1989) established the effect of moisture content (at room temperature) on the properties of solid-sawn structural lumber in bending and in tension parallel to grain for the normal range of moisture content (from about 10% to green). This information was recently extended to extremely low moisture content for both solid-sawn and composite lumber products tested in bending and in tension parallel to grain (Green and Evans 2003).

Information on the immediate effect of temperature on the properties of solid-sawn lumber is presented in Barrett and others (1989). In 1999, a model was developed for adjusting the modulus of elasticity (MOE) of lumber for temperature changes from −26°C to 66°C (−15°F to 150°F) for lumber with 12% to green moisture content (Green and others 1999). This model has recently been extended to lumber with moisture content as low as 4%.[1]

Permanent Effect of Temperature

A series of studies on the permanent effect of temperature began in 1989 as a result of inquires from knowledgeable professionals (primarily consulting engineers) about problems observed in wooden structures. The calls were infrequent but persistent, and they indicated that current design advice may be insufficient. All inquiries involved commercial or industrial buildings. In the process of exploring research on the permanent effects of temperature, we discovered that requests for additional information on this subject had long been sought by consulting engineers (see, for example, discussions by R.M. Powell in Meyer and Kellogg (1982), p. 19). Nonetheless, there was little support for mounting a major study on the permanent effects of temperature on the mechanical properties of lumber.

One major obstacle to such a study was the high cost of a chamber capable of reaching high temperatures and humidity levels and devoted to one project over a long period. In the 1980s, problems began to be reported with the use of fire-retardant-treated plywood (LeVan and Collet 1989). This provided the impetus for FPL to purchase a chamber devoted to long-term temperature studies at 62°C (144°F) and 75% RH. This chamber had enough space for both southern pine plywood and clear specimens for the fire-retardant-treated wood studies and for lumber for our proposed lumber studies. No FPL operating dollars were available for the purchase of lumber. However, the Weyerhaeuser Corp. and Trus Joist, A Weyerhaeuser Business (at that time an independent company), provided Spruce–Pine–Fir (SPF) machine-stress-rated (MSR) lumber and southern pine, Douglas-fir, and yellow-poplar laminated veneer lumber (LVL) for the proposed study. The decision to use MSR lumber was driven by the thought that only the middle to higher grades of visually or mechanically graded lumber were likely to be used in the long-span members typical of many industrial buildings.

[1] Green, D.W.; J.W. Evans. Predicting the immediate effect of temperature on the modulus of elasticity of lumber. Submitted for publication in Holzforshung.

The exposures for the initial study involved four combinations of temperature and moisture content:

1. 66°C (150°F) and 75% RH (expected equilibrium moisture content (EMC) of 12%), Table 1
2. 82°C (180°F) and 30% RH (expected EMC of 4%), Table 2
3. 82°C (180°F) and 80% RH (expected EMC of 12%), Table 3
4. 66°C (150°F) and 25% RH (expected EMC of 4%), Table 4

In the following discussion, these four sets of exposures are called the primary studies. Over the years, some material has been added to some of these exposures. Studies of limited scope have also been added to the program. These supplementary studies have sometimes been instigated by the desire to use pieces left over from sorting the lumber into groups for the primary studies to gain some background on other concerns. At other times, they have been prompted by a question that arose during the course of the primary studies that could be addressed by a limited scope study. The limited scope studies will collectively be called "side studies."

Primary Studies

Chamber space, funding limitations, and workload considerations dictated that sample sizes for the primary studies be held to a minimum. Estimations of sample sizes given material variability, plus the knowledge that we would be looking for mean trends over time of exposure, led us to decide that the smallest sample size could be 30 pieces for solid-sawn lumber and 15 pieces for composite lumber products. These same limitations dictated that we could test in only one failure mode. Clear wood studies reported in the literature indicate that tension parallel to grain is less sensitive to temperature than is bending, and so we decided to test the lumber in bending.

Another consideration was whether to test all lumber at room temperature and 65% RH or to test at the same expected RH level to which the lumber was exposed during the temperature exposures. We decided to test the exposed specimens at the same expected moisture content levels to which the lumber had been exposed, so that the data would correspond as closely as possible to how wood is exposed in structures, where members are under load at an elevated temperature for long periods. Thus, our data would include both immediate and permanent effects measured at conditions that most closely correspond to those of wood in service.

The practice of exposing and testing wood at the same humidity is in contrast to the procedures of LeVan and others (1990) and Winandy (2001), where the wood was exposed at various temperature and humidity conditions but all pieces were tested at approximately 23°C (73°F) and 65% RH. This was the logical procedure for these studies

Table 1—Experimental design for condition 1, 66°C (150°F) and 75% RH

Product	Species	Grade	Sample size by exposure period (months)										
			0	6	10.4	12	18	24	28	32	36	48	68
Solid-sawn	SPF	1650f–1.5E	31	31	—	31	—	30	—	—	30	31	32
	Douglas-fir	2100f–1.8E	30	30	—	30	—	30	—	—	30	29	30
		1800f–1.8E	29	—	—	—	—	—	—	—	15	15	—
		2400f–2.0E	29	—	—	—	—	—	—	—	15	15	—
	Southern pine	MSR	52	—	—	—	—	—	—	—	52	—	—
LVL	Douglas-fir	2.0E	15	15	—	15	—	15	—	—	15	14	14
	Southern pine	2.0E	16	16	—	16	—	16	—	—	15	15	18
	Yellow-poplar	2.0E	16	17	—	15	—	16	—	—	15	13	18
LSL[a]	Aspen	1.3E	15	13	—	—	13	—	15	—	—	—	—
	Yellow-poplar		14	—	14	—	12	—	—	13	—	—	—

[a]LSL, laminated strand lumber.

because their primary initial objective was to understand the mechanisms causing fire-retardant-treated wood to fail. Eliminating the added variability that would have been introduced by testing at different humidity levels enabled the studies to focus on the basic mechanisms causing wood degradation. Thus, the scientists involved in the two series of primary studies made different decisions based on their overall objectives. This is often the case in science, and users of research must keep these differences in mind so as not to use the results for inappropriate applications. Skarr (1976) provides a useful discussion of this conundrum with respect to the effect of high temperature drying on the properties of lumber. In the end, there is no "correct" approach; for some applications of research results, it may be necessary to account for procedural differences in the studies.

The lumber initially obtained for the primary studies was divided into groups based on MOE determined by transverse vibration (E_{TV}) within individual grades or product types. Because only one chamber was initially available, the senior author, in consultation with Jerrold Winandy, who was conducting most of the experimental studies at that time on fire-retardant-treated plywood, decided to start with condition 1, 66°C (150°F) and 75% RH. The lumber for the other three conditions was stored until additional chamber space became available. Condition 1 was selected for the initial study because 66°C (150°F) is a reference temperature listed in the National Design Specification (AF&PA 1997) (see discussion in Green and Evans 2001a) and because the literature shows that the permanent effects of temperature are likely to be higher at high humidity levels than at low levels. As funds became available, we included Douglas-fir and southern pine solid-sawn MSR lumber in the study.

Table 1 shows the experimental design for condition 1. Douglas-fir and southern pine solid-sawn lumber were added to the study after the chamber had been in operation for almost 2 years. Thus, the exposure times for these species are shorter than those for the Spruce–Pine–Fir (SPF) and laminated veneer lumber (LVL). The results of this study are presented in Green and Evans (2001a) and Green and others (2003).

A few years later, a second conditioning chamber became available for studies at condition 2, 82°C (180°F) and 30% RH (Table 2). By then, the experimental data on solid-sawn lumber from condition 1 had indicated that grade has little effect on the change in MOR over time of exposure. Thus, by cutting the sample size in half for the solid-sawn lumber, we were able to obtain mean trends after both 12 and 24 months exposure. Unfortunately, a large amount of LVL and some solid-sawn lumber was lost through experimental problems with the smoldering of caulking. At the conclusion of the condition 3 exposure (82°C (180°F), 80% RH, Table 3), "new" solid-sawn lumber was added to the chamber and the conditions were reset to condition 2. The results for condition 2 for the original set of lumber are presented in Green and others (2003). Results for the new material exposed to condition 2 will be published when the exposures are completed in about 1-1/2 years. The results for condition 3 (82°C (180°F), 80% RH) are presented and discussed here.

About the same time the exposures for condition 1 were started, we manufactured an insulated box that could be used for condition 4 (66°C (150°F), 25% RH, Table 4). The commercial humidity chamber that had been used for condition 4 (82°C (180°F), 30% RH) was old; we were only able to get about 1 year of continuous exposure before the equipment broke down. The lumber remained in the chamber for approximately 3 years while we tried various options for completing the study. At the completion of the exposures for condition 1, we reset that chamber to 66°C (150°F) at 25% RH and moved the original sample to the chamber. We

Table 2—Experimental design for condition 2, 82°C (180°F) and 30% RH

				Sample size by exposure period (months)					
Data set	Product	Species	Grade[a]	0	10	13	20	21	30
Original	Solid-sawn	SPF	MSR	30	—	—	—	18	—
		Douglas-fir	1800f–1.8E	30	—	—	—	25	—
			2400f–2.0E	29	—	—	—	30	—
		Southern pine	MSR	52	—	—	—	52	—
	LVL	Douglas-fir	2.0E	15	—	—	—	5	—
		Yellow-poplar	2.0E	16	—	—	—	7	—
	LSL	Aspen	1.3E	15	—	—	15	—	—
		Yellow-poplar	1.5E	14	—	14	—	—	—
New	Solid-sawn	Douglas-fir	SS	61	28	—	29	—	29
		Southern pine	2250f–1.9E	90	30	—	30	—	30
		Southern pine	2700f–2.2E	60	28	—	28	—	28

[a] SS is Select Structural.

Table 3—Experimental design for condition 3, 82°C (180°F) and 80% RH

			Sample size by exposure period (months)					
Product	Species	Grade	0	2	5	8	12	24
Solid-sawn	SPF	MSR	61	—	—	—	30	—
	Douglas-fir	1800f–1.8E	29	—	—	—	15	14
		2400f–2.0E	29	—	—	—	15	15
	Southern pine	MSR	52	—	—	—	51	—
		2250f–1.9E	14	—	—	—	15	15
	Yellow-poplar	Ungraded	18	—	—	—	18	—
LVL	Douglas-fir	2.0E	15	—	—	—	14	—
	Southern pine	2.0E	16	—	—	—	16	—
	Yellow-poplar	2.0E	16	—	—	—	16	—
LSL	Aspen	1.3E	15	—	13	—	13	—
	Yellow-poplar	1.5E	14	14	—	14	14	—

Table 4—Experimental design for condition 4, 66°C (150°F) and 25% RH

				Sample size by exposure period (months)					
Data set	Product	Species	Grade	0	6	12	24	36	48
Original	Solid-sawn	SPF	MSR	30	—	—	—	30	—
		Douglas-fir	1800f–1.8E	27	—	—	—	27	—
			2400f–2.0E	30	—	—	—	30	—
		Southern pine	MSR	52	—	—	—	52	—
	LVL	Douglas-fir	2.0E	15	—	—	—	15	—
		Southern pine	2.0E	16	—	—	—	16	—
		Yellow-poplar	2.0E	16	—	—	—	16	—
New	Solid-sawn	Douglas-fir	SS	61	—	—	29	29	—
		Southern pine	2250f–1.9E	90	—	—	59	60	59
			2700f–2.2E	60	—	28	28	56	—
	LVL	Douglas-fir	1.9E	15	—	—	15	15	15
		Southern pine	1.9E	15	—	—	15	15	15
		Yellow-poplar	1.9E	15	—	—	15	15	15
	LSL	Aspen	1.5E	15	15	15	15	15	—
		Yellow-poplar	1.5E	15	15	15	15	15	—

Table 5—Sample sizes for estimating total strength loss at 66°C (150°F) and 75% RH from immediate and permanent effects

			Sample size by exposure period and temperature			
			0 months		36 months	
Product	Species	Grade	Room temperature	Elevated temperature	Room temperature	Elevated temperature
Solid-sawn	SPF	1650f–1.5E	31	30	30	31
		2100f–1.8E	30	30	30	30
LVL	Douglas-fir	2.0E	15	15	15	14
	Southern pine	2.0E	16	16	15	15
	Yellow-poplar	2.0E	16	16	15	16

Table 6—Sample sizes for estimating cumulative effect of thermal degradation on properties of solid-sawn lumber at 82°C (180°F) and 30% RH

			Sample size by exposure period (months)			
Exposure	Species	Grade	0	10	20	30
Continuous	Southern pine	2250f–1.9E	90	30	30	30
		2700f–2.2E	60	28	28	28
Cyclic[a]	Douglas-fir	SS	61	28	29	29
	Southern pine	2250f–1.9E	90	—	—	30
		2700f–2.2E	60	28	28	28
	Douglas-fir	SS	61	29	29	29

[a] Length of exposure condition is half elapsed time for exposure.

also placed additional solid-sawn and composite lumber in the chamber. This allowed us to both check on the results obtained with the original sample and obtain more complete results for solid-sawn and composite lumber products. The last of these exposures should be completed in about 1-1/2 years and will be published when analysis is complete.

Side Studies

Additional information on the permanent effects of temperature on lumber properties was obtained through four side studies. The first side study evaluated our ability to estimate the total effect of temperature given knowledge about both immediate and permanent effects. This study was only conducted at 66°C (150°F) and 75% RH using SPF solid-sawn lumber and Douglas-fir, southern pine, and yellow-poplar LVL (Table 5). The results are presented in Green and others (2003), but will be discussed further in the Results section of the work reported here.

A second side study investigated the permanent effect of temperature on the flexural properties of LVL tested flatwise. All the LVL tested in the primary studies was broken in an edgewise orientation. In the second side study, we hoped to discover the extent to which the results from the primary study are applicable to LVL loaded flatwise. Douglas-fir LVL was exposed at 82°C (180°F) and 80% RH (see Results). Southern pine and yellow-poplar are currently being exposed at 66°C (150°F) and 25% RH, and the results will be published after 3 years of continuous exposure. There are generally only six specimens per species and exposure condition for this side study.

A third side study is evaluating if the properties of thermally degraded laminated strand lumber (LSL) can be determined using a small 43- by 43-mm (1.7- by 1.7-in.) specimen instead of a full 2 by 4 specimen. This study is limited to aspen LSL but includes exposure at both 66°C (150°F)/25% RH and 82°C (180°F)/80% RH. The sample for the small specimens in this study consists of approximately 15 pieces per exposure period. The results for the 82°C (180°F)/80% RH exposure, for exposures up to 12 months, are discussed here; those at 66°C (150°F)/25% RH, for exposures up to 24 months, will be discussed in a future paper.

A fourth side study is investigating how to estimate the effects of intermittent (cyclic) exposure to high temperatures (Table 6). When estimating the permanent effect of cyclic exposure, it has traditionally been assumed that one can sum the total time at the higher temperature and that the effect is equivalent to a continuous exposure of the same period. The few studies of which we are aware that have attempted to examine this assumption have not resulted in satisfactory answers, often because of experimental problems. Our cyclic study is limited to solid-sawn lumber but includes both 2250f–1.9E and 2700f–2.2E southern pine MSR and Select Structural Douglas-fir. Sample size is approximately 30 per species group and exposure. However, larger samples sizes will be available for the unexposed control groups. Continuous exposure periods are 10, 20, and 30 months. Cyclic specimens are left at 82°C (180°F) for 1 month and then moved to a chamber at 20°C (68°F) and 25% RH for a month before being returned to the higher temperature. Thus, at the end of each exposure period, the cyclic-exposure specimens will have been exposed to the higher temperature for half the time as are the continuous-exposure specimens, and the transition from 82°C (180°F) at an expected 4% moisture content to room temperature at an expected 4% moisture content will be abrupt. This side study will be completed in about 1-1/2 years.

The fifth, and final, side study will attempt to investigate some other fundamental aspects of lumber failure mechanisms through a limited number of tests on clear wood specimens cut from undamaged ends of solid-sawn specimens that were tested in bending in the primary studies. We are planning to test clear wood specimens in mode I fracture, compression perpendicular to grain, and block shear. Because of problems encountered in trying to keep broken lumber specimens over an 18-year period, data from this side study may not cover all exposure conditions and periods. These results will be available after the primary studies have been completed.

Procedures

Primary Studies

All solid-sawn lumber used in the primary studies was 2 by 4 lumber obtained from commercial production. Two MSR grades of solid-sawn Spruce–Pine–Fir (SPF) lumber, 1650f–1.5E and 2100f–1.8E, were obtained from a mill in Vancouver, British Columbia. The Douglas-fir was solid-sawn 1800F–1.8E and 2400F–2.0E MSR lumber obtained from a mill in central Oregon. The solid-sawn southern pine “MSR” grade was a mixture of several MSR grades with assigned MOE values between 1.6E and 2.0E. This lumber was taken from existing stock at the FPL. The southern pine 2250f–1.9E and 2700f–2.2E lumber was also taken from existing FPL inventory.

Three species of LVL were used: Douglas-fir, southern pine, and yellow-poplar. All LVL was approximately 89 mm (3.5 in.) wide. Thickness of southern pine and yellow-poplar LVL averaged 43 mm (1.7 in.) and that of Douglas-fir 38 mm (1.5 in.). The LVL tested in the primary study reported here (condition 3) was 2.0E grade and was manufactured with a phenol formaldehyde adhesive. A different batch of LVL with an assigned grade of 1.9E was used in some side studies. Two species of LSL were sampled: aspen (1.3E grade) and yellow-poplar (1.5E). Both LSL species were manufactured using an isocyanate-based adhesive. Average thickness of LSL was 38 mm (1.5 in.) and average width 89 mm (3.5 in.). The aspen LSL used in the side study was also 89 mm (3.5 in.) wide but had an average thickness of 43 mm (1.7 in.); its grade was 1.5E.

The term 2 by 4 lumber, as used in this report, refers to all the lumber, both solid-sawn and composite. After the lumber was conditioned at 23°C (73°F) and 65% RH, nominal 12% moisture content, the flatwise MOE of each piece was obtained by transverse vibration (E_{TV}) (Ross and others 1991). For the exposure portion of the study, each grade of MSR lumber was sorted into 10 groups of approximately 30 pieces each, and each species of LVL and LSL was sorted into 10 groups of approximately 15 pieces each. Matching was accomplished by ranking E_{TV} values from high to low and randomly assigning the first 10 pieces to a treatment group. The next group of 10 pieces was then assigned to a treatment group until all pieces were assigned. Additional groups, matched by E_{TV}, were also obtained for later studies.

An exposure chamber with approximate dimensions of 3.7 by 3.7 by 3.0 m (12 by 12 by 10 ft) was used for conditioning the specimens at 82°C (180°F) (Table 3). Specimens were placed on stickers in the chamber and covered with a sheet of plywood to prevent potential water droplets from falling on the lumber from the ceiling. In addition to a large fan in the ductwork of the exposure chamber, a smaller fan was placed near the hot air intake to help ensure good air circulation. A number of thermocouples were hung from the ceiling at several key positions around the stacked lumber to monitor variations in temperature within the chamber. The temperature in the chamber was generally recorded on Monday and Friday of each week during the exposure period. Except for brief periods when the chamber door was opened, the temperature in the chamber near the lumber stacks varied by less than 3°C (37°F) during the exposure period. Input of outside air in the ventilation ducting of the 82°C (180°F) chamber helped prevent oxygen deprivation in the closed chamber. Following the required exposure period, the lumber was removed from the heating chamber and equilibrated at 23°C (73°F) and 65% RH prior to testing. Control specimens were placed in a room-temperature chamber (23°C, 73°F) at 65% RH and held for testing until the first group of heated specimens was tested.

The MOE of equilibrated specimens was determined by transverse vibration (E_{TV}), with the specimens in flatwise orientation and supported at their ends (Ross and others 1991). Edgewise MOR was determined by ASTM D 198 (ASTM 1999) using quarter-point loading and a span-to-depth ratio of 21:1. Quarter-point loading was chosen to increase the constant moment region over what it would have been for the more traditional third-point loading. The rate of loading was approximately 51 mm/min (2 in.es/min). This rate was chosen because some groups in the overall study were to be tested hot and a faster rate of loading would minimize cooling during testing.

After testing, oven-dry moisture content and specific gravity based on oven-dry weight and oven-dry volume were determined from sections taken near the failure region (ASTM D 2395 and D 4442, ASTM 1999). Specimens were also cut from near the failure region for chemical analysis. To prepare for chemical analysis, several randomly selected pieces from each treatment group were ground to material fine enough to pass a 30-mesh (0.547-µm) screen. Chemical analysis for sugars, acid-soluble lignin, and klason lignin was conducted generally following the procedures of Pettersen and Schwandt (1991), TAPPI method 250 (TAPPI 1982), and Effland (1977). Individual chemical components were determined as a percentage of total weight of wood. Acidity was determined using a pH meter in a water and wood flour solution.

Table 7—Sample size for comparing effects of thermal degradation on flatwise bending of LVL

Exposure condition	Species	Grade	Sample size by exposure period (months) 0	12	36
82°C (180°F), 80% RH	Douglas-fir	1.9E	6	6	—
66°C (150°F), 25% RH	Southern pine	1.9E	6	—	6
	Yellow-poplar	1.9E	6	—	5

Table 8—Sample size for comparing effects of thermal degradation on MOR of small aspen LSL[a]

Exposure period (months)	Sample size by exposure condition: 66°C (150°F) 30% RH	82°C (180°F) 80% RH
0	15	15
2	—	15
5	—	15
6	15	—
12	15	15
24	15	—

[a]Specimens were 43 by 43 by 813 mm long (1.7 by 1.7 by 32 inches long).

Side Studies

Flatwise LVL tests (Table 7) were conducted in static bending using a span of 218 cm (7 ft) for the 243-cm- (8-ft-) long specimen. The load was applied at the quarter-points of the span following recommendations of ASTM D 198 (ASTM 1999).

Bending tests on small (43- by 43- by 813-mm-long, 1.7- by 1.7- by 32-in.-long) aspen specimens (Table 8) were conducted using a center-point load. The 43-mm width was chosen to produce a square cross-section. Care was taken to load the original face of the specimen so that any effects resulting from platen heating or surface consolidation were maintained. Testing procedures generally followed those of ASTM D 198.

Results of Primary Studies

Table 9 summarizes the properties of solid-sawn lumber tested over the course of the study and Table 10 the properties of the composite lumber products. Because of the small sample sizes, the absolute values may or may not be representative of the populations from which they were obtained. Furthermore, the E_{TV} value might be expected to be slightly higher than the value that would have been obtained by static measurement. However, we believe that the relative change in properties following exposure is typical of what might be expected of the lumber types tested and that

Table 9—Properties of solid-sawn lumber tested at 23°C (73°F) and 65% RH after continuous exposure at 82°C (180°F) and 80% RH[a]

Species	Grade	Exposure period (months)	*n*	EMC (%)	Specific gravity (OD/OD)	E_{TV} ($\times 10^6$ lb/in^2)[b] Mean	COV	MOR ($\times 10^3$ lb/in^2)[b] Mean	COV
SPF	MSR	0	61	11.2	0.44	1.717	9.7	7.974	26.5
		12	30	9.5	0.42	1.620	10.7	5.192	35.5
Douglas-fir	1800f–1.8E	0	29	11.6	0.46	1.968	13.0	6.647	35.2
		12	15	9.2	0.45	1.930	6.2	4.010	37.0
	2400f–2.0E	24	14	7.1	0.45	1.937	16.8	4.374	45.5
		0	29	11.8	0.54	2.524	10.5	10.040	28.4
		12	15	9.1	0.54	2.470	12.0	6.698	31.2
		24	15	7.2	0.51	2.435	13.3	5.326	39.3
Southern pine	MSR	0	52	11.2	0.65	2.428	21.6	12.146	35.4
	2250f–1.9E	12	51	9.0	0.61	2.350	18.8	5.849	30.6
		0	14	12.3	0.62	2.348	10.7	9.970	29.7
		12	15	8.9	0.62	2.327	11.8	6.314	31.3
		24	15	6.6	0.58	2.438	11.3	4.988	36.7
Yellow-poplar	Ungraded	0	18	12.1	0.48	1.884	17.1	10.151	10.9
		12	18	8.7	0.46	1.974	9.4	6.650	46.2

[a]EMC is equilibrium moisture content; COV is coefficient of variation.
[b]1 lb/in^2 = 6.895 kPa.

Table 10—Properties of composite lumber products tested at 23°C (73°F) and 65% RH after continuous exposure at 82°C (180°F) and 80% RH

Product and species	Grade	Specific gravity (OD/OD)	n	EMC (%)	Specific gravity (OD/OD)	E_{TV} Mean ($\times 10^6$ lb/in^2)[a]	E_{TV} COV (%)	MOR Mean ($\times 10^3$ lb/in^2)[a]	MOR COV (%)
Laminated veneer lumber									
Douglas-fir	2.0E	0	15	8.7	0.52	2.370	5.7	8.957	10.5
		12	14	10.8	0.52	2.108	8.7	5.060	13.5
Southern pine	2.0E	0	16	9.3	0.62	2.926	5.7	11.391	10.5
		12	16	12.1	0.62	2.071	8.1	4.687	18.1
Yellow-poplar	2.0E	0	16	8.5	0.50	2.174	5.4	10.678	9.3
		12	16	9.8	0.49	1.852	4.9	4.182	12.7
Laminated strand lumber									
Aspen	1.3E	0	15	8.9	0.61	1.609	5.3	6.808	6.0
		5	13	9.1	0.59	1.480	8.0	3.551	11.4
		12	13	8.1	0.56	1.468	5.9	2.662	7.6
Yellow-poplar	1.5E	0	14	9.0	0.69	1.675	6.3	7.510	13.6
		2	14	9.6	0.63	1.470	8.3	5.339	15.6
		8	14	9.0	0.64	1.358	7.0	3.636[b]	25.0[b]
		12	14	8.4	0.64	1.468	8.3	3.643	13.8

[a]1 lb/in^2 = 6.895 kPa.
[b]If one very low MOR value were dropped, the mean MOR would be 3.82×10^3 lb/in^2 (263.4 kPa) with a COV of 16.0%.

the change in E_{TV} relative to the original will be the same for different flexural modes. Although not addressed in the study reported here, a recent study demonstrated that the percentage of change in flatwise dynamic MOE and edgewise static MOE is virtually identical for the reversible effect of temperature on properties (Green and others 1999).

Equilibrium Moisture Content

For solid-sawn lumber, average equilibrium moisture content (EMC) of the specimens after 1 year of exposure was 2.6% lower than that of the control specimens when both were equilibrated in the same chamber (Table 9). These results were obtained despite the fact that scheduling conflicts for available testing machines usually required that the specimens be left in the chamber for several months longer than would normally have been expected to reach their target EMC. This decrease in hygroscopicity is a well-known effect of heating wood over long periods (Stamm 1964, Skaar 1976). The effect was greater than that observed for the specimens at 66°C (150°F) and 75% RH (condition 1) reported previously. For those specimens exposed for 2 years, the additional exposure resulted in a further drop in EMC of about 2.2%. Surprisingly, EMC of the LVL was about 2% higher after 1 year of exposure than the EMC of the unheated controls (Table 10). This trend is inconsistent with our expectations and with previous results (Green and others 2003). We will monitor this trend in future studies, although the small differences in moisture content would not affect overall conclusions from the trends in properties over time. With the LSL, EMC was reduced about 0.7% following 1 year of exposure. Because heated lumber and composite lumber products are not expected to reach the same EMC for the same set of exposure conditions, properties were not adjusted to a common moisture content, as MacLean (1954, 1955) and Millett and Gerhards (1972) chose to do.

Modulus of Elasticity in Transverse Vibration

For solid-sawn lumber, little change in E_{TV} occurred over the entire exposure period (Table 9). This is the expected result from historical studies and is also consistent with the results obtained for much longer exposure periods at 66°C (150°F) and 75% RH (Green and others 2003). The LVL had about an 18% loss in E_{TV} after 12 months exposure, but varied considerably by species (Table 10). For LSL, E_{TV} loss was only about 10%. These results are also consistent with those at 66°C (150°F), where LVL exhibited a greater drop in E_{TV} than did solid-sawn lumber and LSL experienced a drop between that experienced by LVL and solid-sawn lumber.

Modulus of Rupture

The solid-sawn SPF and Douglas-fir exhibited about a 36% reduction in MOR (average residual MOR of 0.64) after 1 year of exposure (Table 11). (Residual MOE is the ratio of MOE after exposure to MOE of the unexposed control.) That both species exhibited about the same drop in MOR for equivalent exposure conditions is consistent with the results obtained at 66°C (150°F). The solid-sawn yellow-poplar exhibited a 37% drop in MOR after 1 year of exposure. This is essentially identical to that of Douglas-fir and SPF, as will be discussed further in the Discussion. From the previous study and from a review of the literature (Green and Evans 2001a), we expected the southern pine lumber to be more sensitive to temperature compared with Douglas-fir

Table 11—Residual properties of solid-sawn and composite lumber tested at 23°C (73°F) and 65% RH after continuous exposure at 82°C (180°F) and 80% RH

Product and species	Grade	Exposure period (months)	Residual property	
			E_{TV}	MOR
Solid-sawn lumber				
SPF	MSR	12	0.944	0.651
Douglas-fir	1800f–1.8E	12	0.981	0.603
	2400f–2.0E	24	0.984	0.658
		12	0.979	0.667
		24	0.965	0.530
Southern pine	MSR	12	0.968	0.482
	2250f–2.0E	12	0.991	0.633
		24	1.038	0.500
Yellow-poplar	Ungraded	12	1.048	0.626
Laminated veneer lumber				
Douglas-fir	2.0E	12	0.889	0.565
Southern pine	2.0E	12	0.708	0.411
Yellow-poplar	2.0E	12	0.852	0.392
Laminated strand lumber				
Aspen	1.3E	5	0.920	0.522
		12	0.912	0.391
Yellow-poplar	1.5E	2	0.878	0.711
		8	0.812	0.484
		12	0.876	0.485

or SPF. The southern pine “MSR” sample was more sensitive than the other two softwoods, experiencing a 52% drop in MOR after 1 year of exposure. However, the sample of 2250f–1.9E southern pine MSR experienced a drop in MOR of only 37%. While this conflicting result could be just a random occurrence, it did spur us to add additional southern pine data sets to our remaining exposure trials (see discussion of sampling design in Overall Research Program). After 2 years exposure, Douglas-fir MOR had dropped an average of 41%. However, the results from the 1800f–1.8E Douglas-fir at 24 months exposure seem spurious. This could be a result of problems with the original “matching” of specimens and might be exacerbated by a small sample size.

Figure 1 presents the results for solid-sawn lumber from Table 11 in graphical form. The results for SPF at 66°C (150°F) and 75% RH are shown for comparison. The trends shown in Figure 1 at 82°C (180°F) can be compared with those in Figure 2, which were obtained at 66°C (150°F) and high humidity. Overall, the results indicated a greater reduction in MOR at the higher temperature. Table 12 provides a direct comparison at 12 months exposure. For all species, the residual MOR at 82°C (180°F) and high humidity was lower than that at 66°C and high humidity. There was an additional loss in residual MOR of about 23% for SPF and Douglas-fir and an additional loss of 34% for southern pine MSR. The residual MOR values at 82°C (180°F) and 80% RH were lower than those at 82°C (180°F) and 30% RH. For the high humidity exposure, the reduction in MOR was only about 10% lower for SPF and Douglas-fir than the reduction in MOR at 30% RH; southern pine experienced an approximately 24% lower reduction in MOR.

Table 11 gives the residual values for MOR based on the mean values for LVL given in Table 10. These residual values are shown in Figure 3. Although Douglas-fir LVL seemed to exhibit less of a reduction in MOR than did southern pine LVL, the opposite trend was found at 66°C (150°F) and 75% RH (Green and others 2003). Thus, it is not yet clear if one product is more sensitive to thermal degradation than the other. Based on the average residual MOR for the three species of LVL (0.56), the MOR of LVL dropped about 54% after 1 year of exposure at 82°C (180°F) and 80% RH, about 18% greater than the average drop in MOR for solid-sawn Douglas-fir and SPF for the same exposure period. Numerical comparisons after 1 year exposure are given in Table 12 for various exposure conditions. In a high humidity environment, the residual MOR value was much lower at 82°C (180°F) than at 66°C (150°F) (Fig. 4), with a difference in residual MOR of almost 50%. At 82°C (180°F), the residual MOR at 80% RH was less than that at 30% RH (Table 12). However, the difference for Douglas-fir was much less than that for yellow-poplar. Thus, the difference in results for LVL at the two humidity levels is close to the range of differences observed for solid-sawn lumber. Unfortunately, there are no results for southern pine LVL at 82°C (180°F) and 30% RH (Green and others 2003).

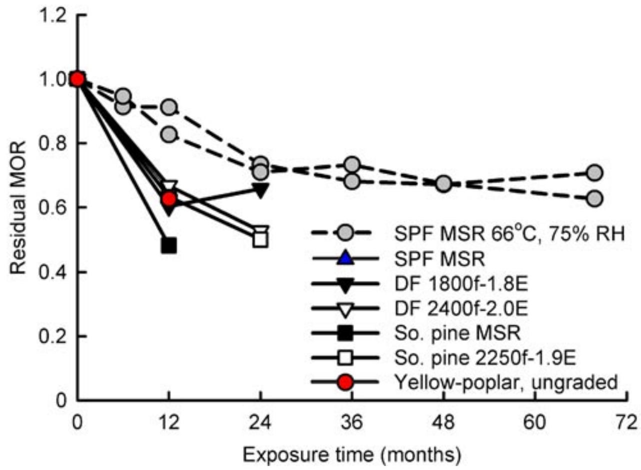

Figure 1—Residual MOR for solid-sawn lumber at 82°C (180°F) and 80% relative humidity (RH); SPF at 66°C (150°F) and 75% RH shown for comparison. SPF is Spruce–Pine–Fir; MSR, machine stress rated; DF, Douglas fir; and So. pine, southern pine.

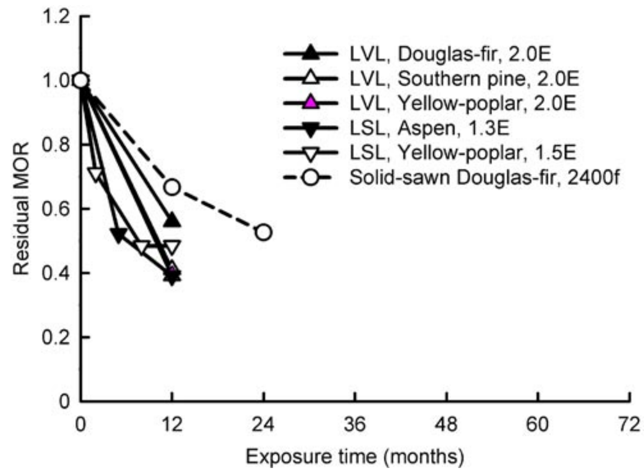

Figure 3—Residual MOR for composite lumber products at 82°C (180°F) and 80% RH; solid-sawn 2400f Douglas-fir at 82°C (180°F) and 80% RH shown for comparison. LVL is laminated veneer lumber; LSL, laminated strand lumber.

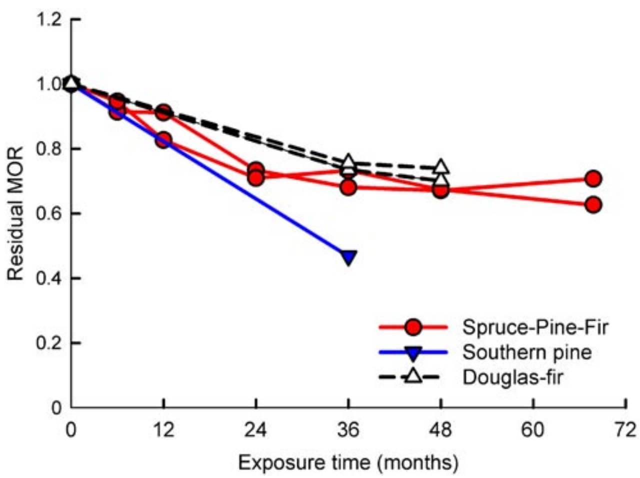

Figure 2—Residual MOR for solid-sawn lumber at 66°C (150°F) and 75% RH (Green and others 2003.)

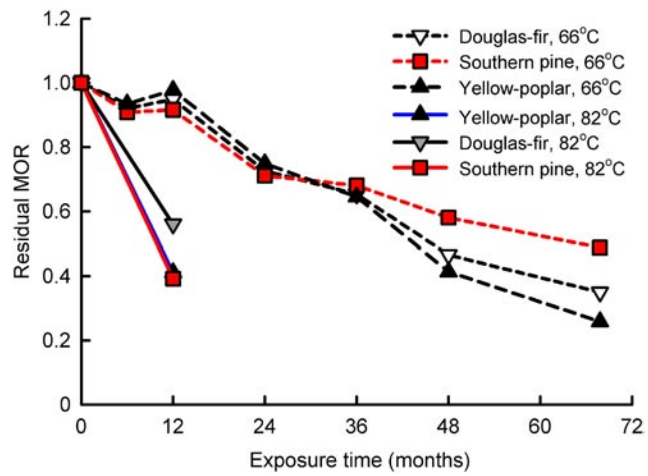

Figure 4—Comparison of temperature effect at 75% to 80% RH for LVL 2 by 4 lumber.

Table 12—Estimated residual MOR values after 12 months exposure under different conditions[a]

			Residual MOR after 12 months exposure at various conditions		
Product	Species	Grade	82°C (180°F) 80% RH	66°C (150°F) 75% RH	82°C (180°F) 30% RH
Solid-sawn	SPF	1650f–1.5E	0.651[b]	0.912	0.758[b]
	Douglas-fir	2100f–1.8E	0.651[b]	0.827	0.758[b]
		1800f–1.8E	0.603	0.870	0.728
		2400f–2.0E	0.667	0.870	0.759
	Southern pine	MSR	0.482	0.822	0.719
LVL	Douglas-fir	2.0E	0.565	0.948	0.622
	Southern pine	2.0E	0.411	0.916	—
	Yellow-poplar	2.0E	0.392	0.977	0.662
LSL	Aspen	1.3E	0.391	0.600	0.676
	Yellow-poplar	1.5E	0.485	0.600	0.713

[a]Where necessary, 12-month exposure was estimated by linear interpolation between adjacent data points.
[b]Samples from each grade combined; listed in original reference as MSR.

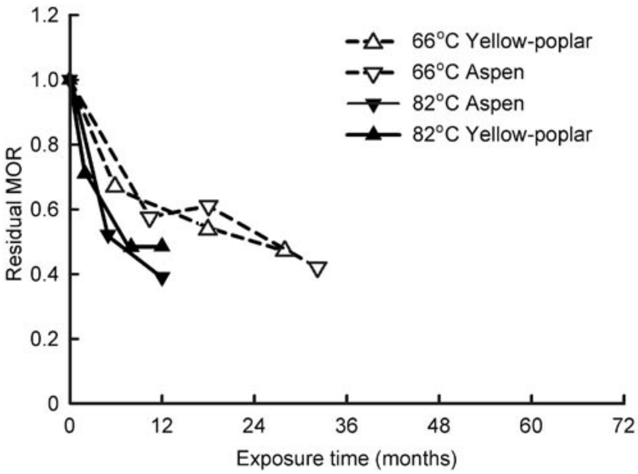

Figure 5—Comparison of temperature effect at 75% to 80% RH for LSL 2 by 4 lumber.

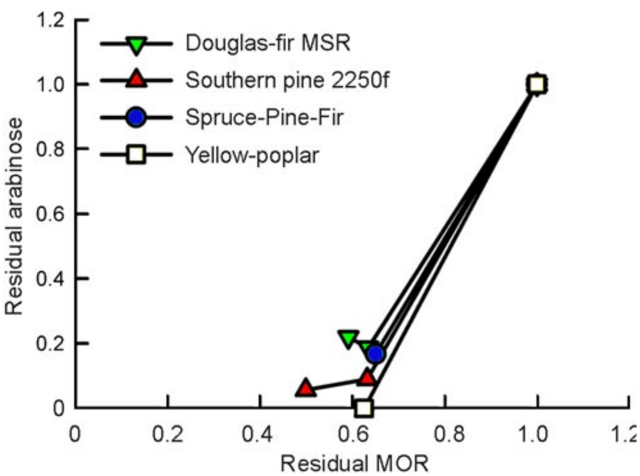

Figure 6—Relationship between residual MOR and residual arabinose for solid-sawn lumber at 82°C (180°F) and 80% RH.

Table 10 shows LSL properties at various exposure intervals. In the original data, one MOR value for yellow-poplar LSL at 8 months exposure was very low (1,233 lb/in^2, 8.5 MPa) compared with the next higher value (3,099 lb/in^2, 21.4 MPa). This low value in a data set of only 14 pieces lowered the mean MOR and increased the coefficient of variation (COV) to a much higher level than in the other data sets. While we found no physical reason to drop this data point from the data set, if that point were arbitrarily dropped, the mean MOR value would increase to 3,820 lb/in^2 (26.3 MPa) and the COV would drop to 16%. The average of the residual value for the two LSL species (aspen and yellow-poplar) after 12 months exposure was 0.44 (Table 11), about the same as the average for LVL of 0.46 but lower than the average for Douglas-fir and SPF solid-sawn lumber of 0.65. At a high humidity level, the residual MOR was lower at 82°C (180°F) than at 66°C (150°F) (Table 12). At both temperature levels there is no indication of any real differences in behavior between the two LSL species, and the relationship between residual MOR and exposure time shows similar patterns for both temperatures (Fig. 5). At 82°C (180°F), the residual MOR averaged 25% lower at 80% RH than at 30% RH. This higher "moisture sensitivity" at high temperature was greater than the "temperature sensitivity" at high humidity and contrasts with the behavior of both the solid-sawn lumber and the LVL, where the opposite trend was observed (Table 12).

Discussion of Primary Studies

Changes in Wood Chemistry

Changes in chemical composition of the 2 by 4 lumber with duration of exposure are shown in Appendix A. Over time, the pH of all products decreased as the material became more acidic. Also for all products, arabinose showed the largest, and most consistent, decrease with time of exposure, sometimes dropping below the detectable limit of 0.01% (percentage of dry weight). As expected, the reduction in arabinose at 82°C (180°F) and 80% RH was greater than that at 66°C (150°F) and 75% RH for an equivalent period of exposure (Green and others 2003). For SPF, for example, at 82°C (180°F) and 80% RH arabinose dropped from 0.95% to 0.16% in 12 months exposure, whereas at 66°C (150°F) and 75% RH, it dropped from 0.95% to 0.85% in 12 months exposure. As discussed by Winandy and Lebow (2001), relationships can be established between change in hemicellulose content and change in MOR. For arabinose, the relationship is generally good (see Fig. 6, for example). However, as indicated by the data in Appendix A and earlier results (Green and others 2003), changes in the other hemicelluloses were quite variable over time for untreated wood, and a distinct trend is often difficult to discern.

As previously noted, MOR of solid-sawn yellow-poplar lumber at 82°C (180°F) and 80% RH was no more sensitive to thermal degradation than was solid-sawn Douglas-fir or SPF lumber (Table 11). It is generally accepted that hardwoods are more sensitive to thermal degradation than are softwoods (FPL 1999, Fengel and Wegener 1984). Industry experience indicates that when heat-soaking logs in preparation for rotary peeling, hardwood logs are soaked for a shorter time than are softwood logs (Kohlmann and others 1975). Thus, the yellow-poplar results might seem unusual. MacLean (1951) found that hardwoods lost more weight during prolonged heating in water than did softwoods (Table 13). However, when the wood was heated in air, the results indicated that weight loss was not necessarily higher for hardwoods than for softwoods. Millet and Gerhards (1972) also found that hardwoods did not necessarily experience a greater loss in MOR when heated in air (Table 14). Thus, these results support our findings. We believe that changes in wood chemistry with thermal degradation can be used to understand the different trends in thermal sensitivity for wood heated in water as compared with heated in air.

Table 13—Relative ranking, from most (1) to least (10) weight loss, of species heated in water and air at indicated temperatures and times[a]

	Relative ranking by heating method, temperature, and time							
	Heated in water				Heated in air			
Species	93°C 5,080 h	120°C 418 h	150°C 141 h	175°C 30 h	93°C 5,080 h	120°C 418 h	150°C 141 h	175°C 30 h
Basswood	1	3	3	2	6	1	1	1
White oak	2	4	4	3	2	3	2	9
Yellow birch	3	1	1	1	4	2	3	5
Yellow-poplar	4	2	5	4	4	5	5	8
Hard maple	5	6	2	6	8	7	4	2
Sweet gum	6	5	6	5	3	4	9	4
Southern pine	7	7	7	7	1	8	6	3
White pine	8	9	8	8	6	9	7	10
Douglas-fir	9	8	9	10	9	10	10	7
Sitka spruce	10	10	10	9	10	6	8	6

[a]Green and Evans (2001a), adapted from data in MacLean (1951). 93°C = 200°F, 120°C = 250°F, 150°C = 300°F, 175°C = 350°F.

Table 14—Relative ranking, from most (1) to least (10) weight loss, of lumber heated in air at indicated temperatures and times[a]

	Relative ranking by temperature and heating period			
Species	115°C 255 days	135°C 64 days	155°C 16 days	175°C 4 days
Southern pine	1	1	1	1
Red oak	2	2	3	4
Western redcedar	3	3	4	2
Sugar maple	4	4	2	3
Ponderosa pine	5	5	5	5
Douglas-fir	6	6	6	6

[a]Green and Evans (2001a), adapted from data in Millet and Gerhards (1972). 115°C = 240°F, 135°C = 275°F, 155°C = 310°F, 175°C = 350°F.

Table 15—Summary of chemical composition of wood (Pettersen 1984)

	Amount of component (% by weight)			
	Average		Range	
Component	Softwood	Hardwood	Softwood	Hardwood
Glucose	44.5	45.8	41–47	38–52
Lignin	29.5	22.6	26–33	19–24
Hemicellulose				
Arabinose	1.4	0.5	0.5–2.7	0.3–0.8
Galactose	2.0	1.1	1.0–4.7	0.1–2.2
Xylose	6.4	17.1	2.8–10	12–26
Mannose	10.6	2.4	8.0–13	1.8–3.6
Acetyl group	1.4	3.8	0.8–2.2	2.9–5.5
Uronic acid	4.1	4.4	2.8–5.4	3.5–5.1

For temperate species, wood is composed of about 40% to 50% cellulose, 20% to 35% lignin, and 12% to 35% hemicellulose, plus extractives (Pettersen 1984) (Table 15). When wood is heated, these components are relatively stable up to about 100°C (212°F) and up to about 48 h of heating (Fengel and Wegener 1984). At higher temperatures and longer heating times, chemical degradation begins to occur. Chemical acid hydrolysis is the most typical degradation mechanism, with hemicelluloses being more sensitive to thermal degradation than is cellulose or lignin (Fengel and Wegener 1984). Because hemicelluloses are composed of shorter chains and have a more branched structure, they are more easily hydrolyzed by acids than is cellulose. Of the hemicelluloses, arabinose and galactose are especially sensitive to thermal degradation (LeVan and others 1990, Winandy and Lebow 2001). As wood degrades, acetyl groups being lost from the chemical structure combine with available water to form acetic acid, which acts as a catalyst to further speed the rate of reaction.

Hardwoods and softwoods differ to only a small extent in the total amount of hemicellulose present, but there are differences in their chemical structure (Fengel and Wegener 1984). Hardwoods actually have less arabinose and galactose than do softwoods, but they have more acetyl groups (Table 15). Thus, hardwoods generally have more acid-forming potential than do softwoods. Heating in water causes wood to swell (or to remain swollen), and thus makes the acetyl groups more accessible and allows freer movement of any acids formed. The presence of liquid water would ensure plenty of liquid to combine with the acetyl groups being lost during decomposition and would facilitate movement of the acids generated. The importance of the accessibility of the hydroxyl groups to water during acid hydrolysis of hemicellulose was recently demonstrated by Tjeerdsma and Militz (2005) for both beech and Scots pine. That beech was also found to be more sensitive to accessibility than was Scots pine also supports our hypothesis. Acid hydrolysis of hemicellulose is not the only source of acid formation during thermal degradation. For example, the generation of resinous acids would be expected from species with high extractive contents, such as pines. Thus, for

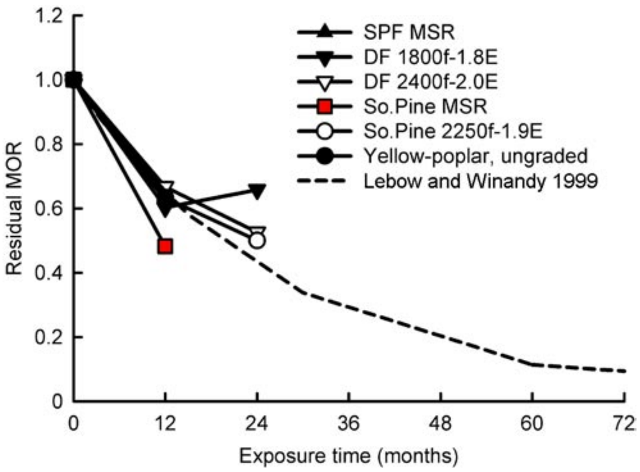

Figure 7—Comparison of residual MOR values for solid-sawn lumber at 82°C (180°F) and 80% RH with analytical model of Lebow and Winandy (1999).

Figure 8—Testing of lumber in 66°C (150°F), 75% RH chamber to determine immediate and total effects of prolonged temperature exposure.

lumber heated in air, it is generally not possible to make blanket statements about the thermal sensitivity of hardwoods compared with softwoods.

Comparison With Analytical Models

As previously discussed (Green and others 2003), there is little agreement between the results of our studies and the predictions from the Arrhenius models developed for solid-sawn wood by Millet and Gerhards (1972). For example, at 66°C (150°F), the Arrhenius equations would predict that a residual MOR of 0.70 would be reached in about 110 years. Our results at 66°C (150°F) and 75% RH showed that a residual MOR of 0.70 would be reached in about 2.5 years. At 82°C (180°F), the Arrhenius model would predict about 15 years to reach a residual MOR of 0.70. Our previous results at 82°C (180°F) and 30% RH indicated that level of residual MOR would be reached in about 1 year (Green and others 2003); the current results at 80% RH indicate that this level would be achieved in less than 1 year. As discussed in our previous papers, two factors must be considered in regard to the Millet and Gerhards study. First, we are using the equations to predict residuals much below the minimum temperature of 115°C (239°F) employed by Millet and Gerhards. Second, and of more importance, the Millet and Gerhards study was conducted to characterize accelerated aging with respect to treating processes, not to evaluate the durability of lumber in structural situations. The specimens in the Millet and Gerhards experiments were exposed in a closed chamber with no outside air intake (Millet and others 1967). This exposure restricted the amount of oxygen available in the chamber; for wood with very low initial moisture content, the exposure led to a much slower rate of degradation than would be experienced with wood heated with adequate air replacement (Stamm 1964, Skaar 1976). Thus, we conclude that using the equations of Millet and Gerhards is not appropriate for normal construction applications.

In previous work (Green and others 2003), we evaluated the kinetics-based models of Lebow and Winandy (1999) for predicting thermal degradation of untreated southern pine. At 66°C (150°F) and 75% RH, the models overestimated our experimental results for solid-sawn southern pine, but at 82°C (180°F) and 30% RH, they predicted our results with great accuracy. In the current study, the kinetics equation overestimated the southern pine MSR data set but underestimated the southern pine 2250f–1.9E data set (Fig. 7). Because of the large variability of our southern pine results, it was not possible to evaluate the applicability of the model to the current southern pine data. To date, this kinetics model is the only one we are aware of that predicts results for solid-sawn southern pine anywhere near those we are obtaining. As additional data become available, we will continue to evaluate the applicability of the model to data sets independent of the data used to derive the model.

Results and Discussion of Side Studies

As noted in the Introduction, some side studies have been completed, some will be reported here, and others are still in progress. The study to evaluate total strength loss resulting from thermal degradation (Table 5) was reported in Green and others (2003) and will be briefly discussed here. The study on estimating the cumulative effect of temperature on strength loss (Table 6) is in progress and will be completed in about 1-1/2 years. Some results from the studies outlined in Tables 7 and 8 are reported here. The remaining studies will be completed in about 1-1/2 years.

Estimation of Total Strength

The permanent effect of heating solid-sawn and composite lumber products at 66°C (150°F) and 75% RH was reported previously (Green and others 2003) (Table 1). The

Table 16—Properties of Douglas-fir LVL tested flatwise after exposure at 82°C (180°F) and 80% RH

Exposure (months)	n	MC (%)	Specific gravity (OD/OD)	MOE ($\times 10^6$ lb/in^2)[a]		E_{TV} ($\times 10^6$ lb/in^2)[a]		MOR ($\times 10^3$ lb/in^2)[a]	
				Mean	SD	Mean	SD	Mean	SD
0	6	10.4	0.483	1.915	0.112	1.905	0.112	6.958	0.681
12	6	10.2	0.472	1.968	0.114	1.883	0.073	4.366	0.908
Ratio	—	—		1.028	—	0.988	—	0.627	—

[a]1 lb/in^2 = 6.895 kPa.

Table 17—Properties of small aspen LSL specimens after exposure at 82°C (180°F) and 80% RH[a]

Exposure (months)	n	MC (%)	Specific gravity (OD/OD)	MOR ($\times 10^3$ lb/in^2)[b]		
				Mean	SD	Residual
0	15	9.3	0.641	7.732	1.215	1.000
2	15	8.8	0.614	5.049	0.971	0.653
5	15	8.0	0.602	4.341	0.622	0.561
12	15	7.6	0.600	3.244	0.394	0.420

[a]Specimens were 43 by 43 by 813 mm long (1.7 by 1.7 by 32 in. long).
[b]1 lb/in^2 = 6.895 kPa.

immediate effect of temperature was also measured for SPF solid-sawn lumber and three species of LVL by removing 2 by 4s from the conditioning chamber one piece at a time and quickly testing them in flexure (Fig. 8). The primary conclusion from this study was that for solid-sawn lumber and LVL, the total effect of temperature could be estimated with good accuracy by adding the reduction in MOR due to the immediate effect of temperature to the reduction due to the permanent effect (1 – residual MOR). Winandy and Rowell (2005) recommend that total effects should be estimated by multiplying the residual value for the immediate effect with the residual value for the permanent effect. The tables in Appendix B present both methods for estimating total effects using the data of Green and others (2003). There is very little difference in the error obtained by either method, and we conclude that either approach could be used. In fact, the most surprising finding is how well the estimates related to the measured total change in MOR for lumber tested at 66°C (150°F) after exposure for 3 years at 66°C (150°F) and 75% RH.

Flatwise and Edgewise Degradation of LVL at 82ºC (180ºF) and 80% RH

Table 16 summarizes the results for Douglas-fir LVL tested in flatwise bending at room temperature and 65% RH after exposure for 12 months at 82°C (180°F) and 80% RH. Static MOE measurements were not taken on previous samples tested edgewise, but both MOE and E_{TV} values were taken on flatwise samples. The ratio of the before-exposure value to the after-exposure (residual) value was 0.988 for the E_{TV} measurement and 1.028 for the static MOE measurement. These values are not statistically different at the 0.05 level and are not different from a value of 1.0. The E_{TV} value for these 6 pieces was 0.988, whereas the flatwise E_{TV} value for the 14 pieces that failed in edgewise bending was 0.890 (Table 11). Because both sets of data are for E_{TV} in the flatwise orientation, the difference between the two residual values is only an indication of the effect of repeating the comparison with a different data set. As would be expected with such small data sets, this 10% difference in E_{TV} values is not significant at the 0.05 confidence level. For MOR, the residual value after 1 year was 0.57 for the edgewise orientation and 0.63 for the flatwise orientation. Again, given the small sample sizes, especially for the flatwise orientation, these differences are not statistically significant at the 0.05 level. Results for 66°C (150°F) and 25% RH will be reported when available.

Use of Small Specimen to Determine Thermal Degradation of LSL

Table 17 summarizes the change in MOR for a 43- by 43- by 813-mm-long (1.7- by 1.7- by 32-in.-long) specimen of aspen LSL. After 12 months exposure at 82°C (180°F) and 80% RH, residual MOR was 0.42. This is virtually identical to the value of 0.391 shown in Table 11 for 38- by 89-mm by 183-cm-long (1.5- by 3.5-in. by 6-ft-long) specimens. Trends in residual MOR with duration of exposure for the two specimen sizes are shown in Figure 9. On the basis of these results, we conclude that a smaller specimen size can be used for this type of product. We again caution, however, that it is likely important that the selected specimen length be at least near to the length of the strands used to manufacture the lumber, and that it may be important to maintain the original surfaces of the lumber product. Results at 66°C (150°F) and 25% RH will be reported when available.

Concluding Remarks

Primary Studies

As expected, thermal degradation at 82°C (180°F) and 80% relative humidity (RH) is the most severe of the three exposure conditions we have reported to date. From the results of the current study we conclude the following:

- As found for modulus of elasticity (MOE) in previous exposure conditions, MOE of solid-sawn lumber is little affected by up to 24 months of continuous exposure. However, the residual MOE of composite lumber products is reduced. After 12 months exposure, the residual

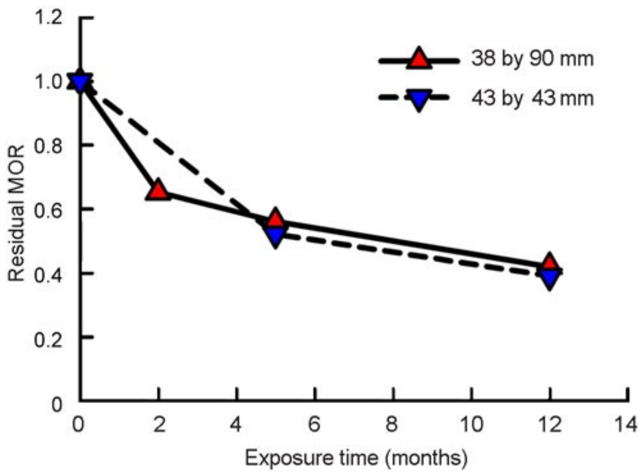

Figure 9—Comparison of residual MOR values for aspen LSL after exposure at 82°C (180°F) and 80% RH.

MOE of laminated veneer lumber (LVL) varied from 0.71 (southern pine) to 0.89 (Douglas-fir) and that of laminated strand lumber (LSL) from 0.88 (yellow-poplar) to 0.91 (aspen).

- As previously observed at other exposure conditions, the residual modulus of rupture (MOR) values of solid-sawn Douglas-fir and Spruce–Pine–Fir (SPF) after 12 months exposure were similar and averaged about 0.64. The residual MOR of one southern pine data set (2250f–1.9E) was about the same as that of Douglas-fir and SPF, with a value of 0.63 after 12 months exposure, but the residual MOR of the other southern pine data set (machine-stress-rated, MSR) was only 0.48.
- After 24 months exposure, solid-sawn Douglas-fir had a residual MOR of 0.53 to 0.66, while 2250f–1.9E southern pine had a value of only 0.50. Thus, although the results at all three exposure conditions are somewhat contradictory, they indicate that southern pine is more sensitive to thermal degradation than are Douglas-fir and SPF, at least at high relative humidity levels.
- After 12 months exposure, the residual MOR of solid-sawn yellow-poplar was 0.63. This result, coupled with a critical review of historical data, indicates that hardwood lumber is not necessarily more sensitive to thermal degradation than is softwood lumber for dry lumber heated in air.
- The residual MOR of composite lumber products was lower than that of solid-sawn Douglas-fir and SPF after 12 months exposure. For LVL, the residual MOR ranged from about 0.39 to 0.56. For LSL, the residual MOR ranged from 0.39 (aspen) to 0.48 (yellow-poplar).
- Despite the reduction in both MOE and MOR that occurs with composite lumber products with 12 months exposure at 82°C (180°F) and 80% RH, MOE is not a good predictor of MOR. There is virtually no correlation between MOE and MOR at this condition; at lower temperature or humidity levels, there is little, if any, change in MOE with temperature.
- As is now well established, acid hydrolysis of hemicellulose, especially of arabinose, appears to be the fundamental cause of strength loss resulting from thermal degradation.

Side Studies

- Based on a small number of tests of Douglas-fir LVL exposed at 82°C (180°F) and 80% RH, the residual MOR in edgewise bending yields a good approximation of the residual MOR in flatwise bending. A study still in progress will address this question for LVL exposed at 66°C (150°F) and 25% RH.
- Tests of aspen LSL exposed at 82°C (180°F) and 80% RH indicated that a small 43- by 43- by 813-mm-long (1.7- by 1.7- by 32-in.-long) specimen had virtually the same residual MOR as a standard 38- by 89-mm by 183-cm-long (1.5- by 3.5-in. by 6-ft-long) specimen. A study in progress will address this question for LSL exposed at 66°C (150°F) and 25% RH.
- A previous study at 66°C (150°F) and 75% RH indicated that the total change in strength for both solid-sawn lumber and LVL tested hot after long-term exposure can be estimated with reasonable accuracy by summing the loss in strength (1 – residual MOR) resulting from the permanent effect of temperature and the loss in strength caused by the reversible effect of temperature. The method of determining total residual MOR by multiplication of the residual MOR resulting from immediate and permanent effects works equally well.

We anticipate that all experimental results will be available in early 2007. Publication of these results and evaluation of analytical models to predict thermal degradation and service life will follow as quickly as possible.

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Literature Cited

AF&PA. 1997. National design specification for wood construction. American Forest & Paper Association, Washington, DC.

ASTM. 1999. Annual book of standards. Vol. 4.10. American Society for Testing and Materials, West Conshohocken, PA.

ASTM D 198. Standard methods for static tests of lumber in structural sizes.

ASTM D 2395. Standard test methods for specific gravity of wood and wood-based materials.

ASTM D 4442. Standard tests methods for direct measurement of moisture content of wood and wood based composites.

Barrett, J.D.; D.W. Green; J.W. Evans. 1989. Temperature adjustments for the North American in-grade testing program. In: Proceedings, In-grade testing of structural lumber, D.W. Green, B.E. Shelley, and H.P. Vokey, eds. Proceedings 47363, Forest Products Society, Madison, WI. p. 27–38.

Effland, M.J. 1977. Modified procedure to determine acid-insoluble lignin in wood and pulp. Tappi J. 60(10):143–144.

Fengel, D.; G. Wegener. 1984. Wood: Chemistry, ultrastructure, reactions. Walter de Gruyter, New York.

FPL. 1999. Wood handbook: Wood as an engineering material. Gen. Tech. Rep. FPL–GTR–113. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. (www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/fplgtr113.htm)

Green, D.W. 1989. Moisture content and the shrinkage of lumber. Res. Pap. FPL–RP–489. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. (www.fpl.fs.fed.us/documnts/fplrp/fplrp489.pdf)

Green, D.W.; J.W. Evans. 1989. Moisture content and the mechanical properties of dimension lumber: Decisions for the future. In: Proceedings, In-grade testing of structural lumber. D.W. Green, B.E. Shelley, and H.P. Vokey, eds. Proceedings 47363, Forest Products Society, Madison, WI. p. 44–55.

Green, D.W.; J.W. Evans. 2001a. Flexural properties of structural lumber products after long-term exposure to 150°F and 75% relative humidity. In: Proceedings, 35th International Particleboard/Composite Materials Symposium, April 3–5, 2001, Pullman, WA. p. 3–15.

Green, D.W.; J.W. Evans. 2001b. Evolution of standardized procedures for adjusting lumber properties for change in moisture content. Gen. Tech. Rep. FPL–GTR–127. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. (www.fpl.fs.fed.us/documnts/fplgtr/fplgtr127.pdf)

Green, D.W.; J.W. Evans. 2003. Effect of low relative humidity on the properties of structural lumber products. Wood Fiber Sci. 35(2):247–265.

Green, D.W.; J.W. Evans; J.D. Logan; W.J. Nelson. 1999. Adjusting modulus of elasticity of lumber for changes in temperature. Forest Prod. J. 49(10):82–94.

Green, D.W.; J.W. Evans; B.A. Craig. 2003. Durability of structural lumber products at high temperatures. I: 66°C at 75% RH and 82°C at 30% RH. Wood Fiber Sci. 35(4): 499–532.

Koehler, A.; Y.Y. Pillow. 1925. Effect of high temperature on mode of fracture of a softwood. Southern Lumberman. 121(1576):219–221.

Kollmann, F.F.P.; E.W. Kuenzi; A.J. Stamm. 1975. Principles of wood science and technology. II. Wood based materials. Springer–Verlag, New York.

Lebow, P.K.; J.E. Winandy. 1999. Verification of a kinetics-based model for long-term effects of fire retardants on bending strength at elevated temperatures. Wood Fiber Sci. 31(1):49–61.

LeVan, S.L.; M.P. Collet. 1989. Choosing and applying fire-retardant-treated plywood and lumber for roof designs. Gen. Tech. Rep. FPL–GTR–62. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. (www.fpl.fs.fed.us/documnts/fplgtr/fplgtr62.pdf)

LeVan, S.L.; R.J. Ross; J.E. Winandy. 1990. Effects of fire retardant chemicals on the bending properties of wood at elevated temperatures. Res. Pap. FPL–RP–498. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. (www.fpl.fs.fed.us/documnts/fplrp/fplrp498.pdf)

MacLean, J.D. 1951. Rate of disintegration of wood under different heating conditions. In: Proceedings, American Wood Preservers' Assoc. 47:155–168.

MacLean, J.D. 1954. Effect of heating in water on the strength properties of wood. In: Proceedings, American Wood Preservers' Assoc. 50:253–280.

MacLean, J.D. 1955. Effect of oven heating and hot pressing on strength properties of wood. In: Proceedings, American Wood Preservers' Assoc. 51:1–23.

Meyer, R.W.; R.M. Kellogg (eds). 1982. Structural use of wood in adverse environments. Society of Wood Science and Technology and Van Nostrand Reinhold Company, New York.

Millett, M.A.; C.C. Gerhards. 1972. Accelerated aging: residual weight and flexural properties of wood heated in air at 115°C to 175°C. Wood Sci. 4(4):193–201.

Millet, M.A.; L.J. Western; J.J. Booth. 1967. Accelerated aging of cellulosic materials: Design and application of a heating chamber. Tappi J. 50(11):74–80A.

Pettersen, R.C. 1984. The chemical composition of wood. In: Rowell, R.M. (ed.), The Chemistry of Solid Wood. Advances in Chemistry Series 207, p. 57–126. American Chemical Society, Washington, DC.

Pettersen, R.C.; V.H. Schwandt. 1991. Wood sugar analysis by anion chromatography. J. Wood Chem. Technol. 11(4):495–501.

Pillow, M.Y. 1929. Effect of high temperatures on the mode of fracture and other properties of hardwoods. Wood Working Industries. 6(4):8–9,30.

Ross, R.J.; E.A. Geske; G.H. Larson; J.F. Murphy. 1991. Transverse vibration nondestructive testing using a personal computer. Res. Pap. FPL–RP–502. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. (www.fpl.fs.fed.us/documnts/fplrp/fplrp502.pdf)

Skarr, C. 1976. Effect of high temperature drying on the rate of degradation and reduction of hygroscopicity of wood. In: Procedings, High-temperature drying effects on mechanical properties of softwood lumber. Madison, WI, February 25–26, 1976. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Stamm, A.J. 1964. Wood and cellulose science. The Ronald Press, New York.

TAPPI. 1982. TAPPI standard useful method 250, acid-soluble lignin in wood and pulp. Technical Association of the Pulp and Paper Industry, Athens, GA.

Tjeerdsma, B.F.; H. Militz. 2005. Chemical changes in hydrothermal treated wood: FTIR analysis of combined hydrothermal and dry heat-treated wood. Holz als Roh-und Werkstoff. 63(2):102-111.

Winandy, J.E. 2001. Thermal degradation of fire-retardant-treated wood: predicting residual service life. Forest Prod. J. 51(2):47–54.

Winandy, J.E.; P.K. Lebow. 2001. Modeling strength loss in wood by chemical composition. Part I. An individual component model for Southern Pine. Wood Fiber Sci. 33(2):239–254.

Winandy, J.E.; R.M. Rowell. 2005. Chemistry of wood strength. Ch. 11, Handbook of wood chemistry and wood composites, R.M. Rowell (ed.) Taylor & Francis, New York. p. 303–347.

Appendix A—Chemical Composition of Lumber After Exposure at 82ºC (180ºF) and 80% RH

Table A1—Chemical composition of solid-sawn lumber

Species	Exposure (months)	pH	Sugar analysis (% dry weight) Arabinose	Galactose	Xylose	Mannose	Glucose
Spruce–Pine–Fir	0	4.5	0.95	2.43	6.80	12.74	45.60
Douglas-fir	12	3.8	0.16	3.17	6.18	10.82	41.34
	0	4.0	0.91	2.76	3.70	12.90	45.09
	12	3.5	0.17	1.77	3.58	13.08	46.54
	24	3.6[a]	0.02	1.71	2.98	11.36	47.30
Southern pine	0	4.1	0.94	2.23	6.00	11.22	42.48
MSR	12	3.8	0.11	2.02	5.28	11.83	43.13
2250f–1.9E	0	4.0	0.88	3.83	6.04	11.10	40.74
	12	3.7	0.08	3.02	5.01	10.55	41.12
	24	3.4	0.05	1.64	3.98	10.54	46.73
Yellow-poplar	0	4.5	0.31	0.46	15.02	2.23	44.86
	12	3.4	<0.01	0.29	14.00	2.80	47.45

[a]Value may be slightly high due to a change in measuring equipment.

Table A2—Chemical composition of composite lumber

Product and species	Exposure (months)	pH	Sugar analysis (% dry weight) Arabinose	Galactose	Xylose	Mannose	Glucose
Laminated veneer lumber							
Douglas-fir	0	6.2	0.95	3.13	3.99	11.60	41.00
	12	4.9	0.11	2.38	3.19	11.45	42.77
Southern pine	0	6.1	1.06	2.10	6.35	11.00	42.90
	12	4.8	0.10	2.09	5.03	10.08	41.85
Yellow-poplar	0	6.4	0.33	0.40	14.60	2.48	43.60
	12	4.5	<0.01	0.27	12.84	2.31	43.92
Laminated strand lumber							
Aspen	0	4.8	0.35	0.53	15.60	1.75	43.60
	5	4.1	<0.01	0.36	15.69	1.67	44.49
	12	3.8	<0.01	0.31	14.58	1.39	46.30
Yellow-poplar	0	4.8	0.35	0.48	15.10	2.59	41.00
	2	4.2	0.23	0.34	14.68	2.10	41.70
	8	3.8	<0.01	0.33	14.81	2.52	43.23
	12	3.7	<0.01	0.30	13.98	2.35	43.23

Appendix B—Estimation of Total Residual MOR and Loss in MOR

Table B1—Estimation of total residual MOR by product of residuals method[a]

		Measured residual		Total residual		Error
Product	Species	Immediate	Permanent	Estimated	Measured	(est–meas)
Solid-sawn	SPF 1650f	0.865	0.681	0.589	0.565	+0.024
	SPF 2100f	0.829	0.733	0.608	0.624	–0.016
LVL	Douglas-fir	0.883	0.654	0.577	0.574	+0.003
	Southern pine	0.833	0.680	0.600	0.547	+0.053
	Yellow-poplar	0.823	0.645	0.531	0.451	–0.080

[a] Data given in Green and others (2003).

Table B2—Estimation of total loss in MOR by sum of losses method[a]

		Measured loss		Total loss		Error
Product	Species	Immediate	Permanent	Estimated	Measured	(est–meas)
Solid-sawn	SPF 1650f	–0.135	–0.319	–0.454	–0.435	+0.019
	SPF 2100f	–0.171	–0.267	–0.438	–0.376	+0.062
LVL	Douglas-fir	–0.117	–0.346	–0.463	–0.426	+0.037
	Southern pine	–0.117	–0.320	–0.437	–0.453	–0.016
	Yellow-poplar	–0.177	–0.355	–0.437	–0.453	–0.016

[a] Data given in Green and others (2003) (losses expressed as percentages).