EFFECT OF CYCLIC LONG-TERM TEMPERATURE EXPOSURE ON THE BENDING STRENGTH OF LUMBER[1]

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Abstract. This research evaluated the historical assumption that repeated exposure to elevated temperatures has a cumulative effect on wood properties. This recommendation was given in a paper by J. D. MacLean in 1951 and is a critical assumption when estimating the permanent effect of temperature on wood properties. No experimental results to support the recommendation were presented by MacLean. Approximately 670 southern pine and Douglas-fir solid-sawn 2×4's of two mechanical grades and one visual grade were subjected to cyclic and continuous exposure at 82°C and 30% RH for periods up to 30 mo. They were then tested after equilibration to room temperature and 20% RH. The cyclic exposure specimens alternated between 1 mo at 82°C and 1 mo at room temperature. The results show that there is no significant difference between the residual modulus of rupture (MOR) of the cyclic and continuously-exposed specimens for equivalent exposure periods. Trends in residual arabinose also supported this conclusion. Plotting the residual MOR of the cyclic specimens as the summation of the time they were exposed to the higher temperature provided a conservative estimate of the permanent effect of temperature. The results discussed in this paper are a small subset of a larger study and are not intended for use in general engineering design.

Keywords: Lumber, high temperature, long-term exposure, cyclic temperature exposure, permanent effects, total effects.

INTRODUCTION

In general, the mechanical properties of wood decrease when heated and increase when cooled. Up to about 100°C, at constant moisture content, the temperature-property relationship is linear and seems reversible if the wood is not heated for prolonged periods. In addition to this reversible effect, if wood is heated to high temperatures for prolonged periods there may also be a permanent, or irreversible, effect. Over the years it has generally been assumed that in normal use (at low moisture content levels) lumber exposed to temperatures up to 82°C for cumulative periods up to 1 yr does not require a reduction in properties to account for permanent temperature effects (for additional discussion see Green et al 2003; Craig et al 2006). Thus in engineering use, a "prolonged" period would be exposure greater that 1 yr. Conversely, a "short" period would be exposure less than 1 yr. If wood is exposed to high temperatures for prolonged periods of time and is tested at the elevated temperature, the expected reduction in strength would be estimated from the combination of both the reversible and the irreversible effects.

There are various service conditions where wood may be exposed to sustained high temperatures on either an intermittent or continuous

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basis. Examples of service conditions of this kind include wood used in vats or tanks holding hot liquids, structural members over or under boilers and furnaces, and scaffolding exposed to radiant heat in electrical-power generating facilities. For wooden members heated to 66°C or less for short periods of time, guidance on appropriate adjustment procedures is readily available (eg AF&PA 2005; ASTM D 6570 (2005); ASTM D 1990 (2005); Green et al 1999). For wooden structural members that might be thermally degraded due to continuous exposure to high temperatures over long periods of time, guidance has historically been given in the Wood Handbook (FPL 1999). In recent years new research has begun to provide additional information on the properties of thermally-degraded structural members in ambient environments (Winandy and Rowell 2005; Green et al 2003, 2005). However, the Wood Handbook remains the only source of guidance in the United States for structural members exposed to cyclic (also called intermittent) exposure for long periods of time. The 1999 edition of the Wood Handbook states that "Repeated exposure to elevated temperature has a cumulative effect on wood properties. For example, at a given temperature the property loss will be about the same after six 1-mo exposures as it would be after a single 6-mo exposure." No further information is provided, and a specific reference for the source of this statement is not given. This is a critical assumption when assessing the effect of cyclic temperatures on residual lumber strength and when estimating thermal degradation when exposed to multiple temperature regimes.

The objectives of this study were to determine the basis for the historical recommendation given in the Wood Handbook that the effects of cyclic exposure to high temperatures over long periods of time are cumulative, and to determine the validity of this assumption for solid-sawn 2×4's at low moisture contents. This paper is part of a larger program to evaluate the thermal durability of structural lumber products (Green et al 2003, 2005).

BACKGROUND

In discussing the permanent effect of temperature on mechanical properties of wood, the 1955 edition of the Wood Handbook (FPL 1955) states that repeated exposure to elevated temperature has a cumulative effect on wood properties. As an example, it is stated that if wood at particular moisture content is exposed six different times to a temperature of 82°C for 1 mo each, the overall effect would be approximately the same as for a single exposure of 6 mo. This is essentially the same as the statement in the current Wood Handbook (FPL 1999) except the reference to a specific temperature is replaced with the words "at a given temperature."

J. D. MacLean

All references to the permanent effect of temperature on wood properties in the 1955 Wood Handbook are to the research of MacLean (1945, 1951, 1953). No earlier references to research on the cumulative effect of cyclic temperature exposure have been found in FPL records. While not the first to study thermal degradation in wood (eg Stamm 1964), MacLean conducted some of the most comprehensive studies of wood subjected to various environmental conditions. Only his 1951 study addressed the effects of intermittent vs continuous exposure on wood properties. In this study, 4 specimens for each of 44 hardwood and softwood species were used for each test condition and time. The specimens were 25 × 25 × 152 mm. Specimens were heated in steam at 5 temperatures ranging from 121–177°C, and in water or an oven at 4 temperatures ranging from 93–177°C. The length of the heating period for the continuous heating portion of the study varied with the heating medium and exposure temperature, but the period was up to 17.5 da in steam, up to 212 da in water, and up to 470 da in an oven. Weight loss was used as the indication of thermal degradation. All specimens were oven-dried at the beginning of the experiment and again after each exposure period.

To study the rate of weight loss with intermittent heating in steam and in water, the specimens were periodically removed, oven-dried, weighed, and returned to the respective heating medium. Weighing intervals were ≥5 h, depending on the temperature used and the total time they had been heated. From these results, MacLean concluded that intermittent steaming and drying caused more rapid deterioration than continuous steaming at the same temperature and exposure period. Further, the difference appeared to be greater with a higher exposure temperature. He stated that "the more rapid weight loss when the specimens were weighed at more frequent intervals was probably due to the fact that oxygen was taken up by the wood when it was oven-dried, so that (for intermittent steam exposure) oxidation and hydrolysis were active in causing disintegration. Naturally, less oxygen was present when steaming was present." No results are presented in the document comparing intermittent vs continuous heating in an oven. It is stated, however, that "since specimens heated in the oven were in contact with the air during the entire heating period, the frequency of weighing did not affect the results." No information or discussion is presented on the cumulative effect of intermittent heating on thermal degradation, and the discussion is limited to one sentence. The traditional recommendation given in the Wood Handbook that the effects of cyclic exposure are cumulative follows directly from MacLean's statement that the frequency of weighing did not affect the results for wood heated in an oven.

G. L. Moore

Moore (1983) evaluated the effect of long-term temperature cycling on the strength of wood for periods up to 3 yr. In this experiment 20- × 20- × 300-mm specimens of Scots pine ("redwood"), Norway spruce ("whitewood"), and hemlock were matched within a species to provide sufficient material so that 12 specimens could be tested for all continuous or intermittent heating periods. A 24-h heating cycle was used to simulate the effect of wood being subjected to domestic heating equipment (Fig 1). For each

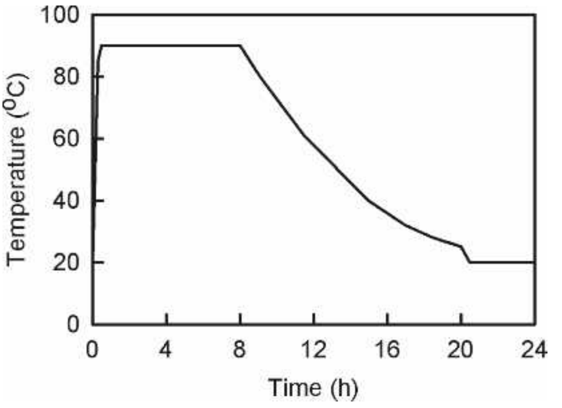

FIGURE 1. Twenty-four hour temperature cycle used by Moore (1983)

cycle, the heating to 90°C took approximately 0.5 h, and was followed by a further 8 h of constant temperature before the heat was switched off. The cooling was a gradual process due to good insulation of the oven. The door was opened toward the end of the cycle to allow the specimens to reach 20°C. The specimens were subjected to dry heat, and no attempt was made to control moisture content. At the end of the required heating period, specimens were tested in center-point bending. One set was tested at 90°C in a heated chamber and the other at 20°C. It was noted that the moisture content of the 20°C specimens had risen to between 1–2% during the cooling period, but this was ignored in making comparisons. An additional set of specimens was exposed continuously at 90°C for 8 mo, stated to be equivalent to cumulative period at 90°C after 3 yr of cyclic exposure.

Table 1 shows the residual strength and stiffness of Moore's specimens for the sets tested at 20°C relative to the properties after 1 da of exposure. Differences between species for these two prop-

TABLE 1. *Residual properties of clear wood after exposure to 24-h temperature cycle to 90°C shown in Fig 1 (Moore 1983).*

	Period of Cyclic Exposure (yr)		
Residual Property[1]	1	2	3
MOR	0.96	0.88	0.76
MOE	1.01	0.98	0.93

[1] Compared with control exposed for 1 da

erties were not significant; thus the ratios are based on the averages for all three species. For specimens heated continuously for 8 mo, the residual MOR values were 0.86, 0.95, and 0.84 for the pine, spruce, and hemlock, respectively. The average of these 3 values is 0.88. Moore notes that a strict comparison between the effects of continuous heating and cyclic heating cannot be made because the slow cooling period for the cyclic heating resulted in a greater overall exposure to elevated temperature. However, he also states that the strength loss found with the 8-mo continuous heating (residual MOR of 0.88) was not as great as that from 3 yr of cyclic heating (residual MOR of 0.76). Moore (2003) has pointed out that there is an error in the paper: 8 mo of continuous exposure is equivalent to 2 yr of cyclic exposure, not 3 yr. Thus if we disregard potential degradation during the period of slow cooling, the average residual MOR for cyclic and continuous exposure would be the same (0.88).

PROCEDURES

The lumber used in this study was solid-sawn 38 × 89 mm (hereafter called 2×4's) obtained from commercial production. The original group of lumber was southern pine machine stress rated (MSR) lumber graded as 2250f-1.9E. For this grade we had only enough lumber for one period of cyclic exposure (30 mo). Later we purchased additional southern pine MSR lumber in grade 2700f-2.2E and visually-graded Select Structural Douglas-fir so that we could have some intermediate exposure specimens for the groups to be cycled. The lumber was then sorted into the required number of groups for each species-grade combination using MOE determined by transverse vibration, E_{TV} (ASTM D6874, 2005) (Table 2). This was accomplished by ranking E_{TV} values with each combination from high to low. For most species-grade combinations seven exposure groups were required. Thus the seven pieces with the highest E_{TV} values were randomly assigned to a group, one piece per group. This was repeated with successive groups of seven pieces until all pieces were assigned to a treatment group. Because there was less 2250f-lumber available, only five exposure groups were used (a control group, three groups for continuous exposure, and one group for cy-

TABLE 2. *Mechanical properties of solid-sawn lumber exposed continuously or intermittently at 82°C, 30% RH for various periods and tested at room temperature at the indicated moisture content.*[1]

Species	Grade	Exposure (mo)	Exposure Group	N	MC (%)	SpGr (od/od)	E_{TV} Mean	E_{TV} COV	MOR Mean	MOR COV
Southern pine	2250f	0	Control	90	4.1	0.62	18.67	13.1	89.57	30.3
		10	Continuous	29	3.6	0.65	19.37	13.8	57.59	30.0
		20	Continuous	30	3.6	0.64	18.34	15.0	52.64	34.8
		30	Continuous	30	3.1	0.64	18.48	11.4	49.29	29.7
			Cyclic	30	3.1	0.65	19.17	13.3	52.56	26.0
Southern pine	2700f	0	Control	59	4.6	0.56	16.35	17.3	73.72	35.4
		10	Continuous	29	3.6	0.62	17.46	14.8	52.85	36.6
			Cyclic	28	3.8	0.60	17.70	17.2	60.96	35.9
		20	Continuous	28	3.2	0.54	17.24	16.1	44.51	40.7
			Cyclic	28	3.4	0.61	17.52	17.2	49.63	34.2
		30	Continuous	28	3.1	0.60	17.26	16.1	40.37	31.2
			Cyclic	28	2.9	0.61	17.35	15.2	44.69	27.1
Douglas-fir	Sel.Str.	0	Control	61	5.3	0.44	12.88	19.9	53.61	48.5
		10	Continuous	28	3.4	0.49	14.51	18.6	43.66	42.9
			Cyclic	29	3.5	0.48	14.29	19.9	45.83	45.9
		20	Continuous	29	3.7	0.48	14.24	19.2	40.72	47.1
			Cyclic	29	3.5	0.49	14.19	19.3	38.68	51.4
		30	Continuous	29	2.9	0.48	13.98	22.0	32.26	46.9
			Cyclic	29	3.0	0.48	14.08	18.8	35.62	46.9

[1] N = number of specimens, MC = Moisture Content, SpGr = Specific gravity based on oven-dry weight and volume, E_{TV} = MOE determined by transverse vibration, GPa, MOR = Modulus of Rupture, kPa, COV = coefficient of variation, %.

clic exposure) and thus the lumber was sorted in groups of 5 pieces.

The control groups for this study contained more specimens than did the groups that were to be exposed. Additional material was required for a separate study at 66°C (see Green et al 2005 for a comprehensive discussion of the studies planned for the thermal durability program). Rather than use the same specimens as a control for both studies, a separate set of controls was obtained for the other study. This permitted us to combine the two sets of control specimens. Not only did this increase the reliability of the data from the control sets, but as will be seen, permitted us to evaluate the degree to which our E_{TV}-based matching procedure yielded similar MOR values from the two subsets of control specimens.

Two conditioning chambers were used for this study. The first was a 3.0- × 6.1- × 2.7-m chamber maintained at 82°C and 30% RH. This RH would yield an expected moisture content of 4% in short-term exposure. Lumber to be exposed to this condition was stickered within the chamber, and a number of thermocouples were placed at various positions and heights to assure that we were getting the expected temperature within the stacks. A modest airflow of about 80 m/min was maintained across the stacks within the chamber, and the large double door of the chamber was opened twice a week, all of which assured that there was no oxygen depletion. A second chamber, in another building, was maintained at slightly above room temperature with a 20% RH. This also gave an expected equilibrium moisture content of 4% in short-term exposure. The control specimens, and all the lumber that had completed its required exposure period, was equilibrated in the second chamber prior to testing. Unlike previous studies (eg MacLean 1951; LeVan et al 1996; Moore 1983) we chose to condition the lumber to approximately the same moisture content prior to testing as that the lumber had reached in the elevated temperature chamber. This was felt to be closer to what structural members would experience in an actual building, and also made it less complicated for evaluating how one should accumulate the effects of cyclic temperature exposure. Maintaining equivalent moisture contents in the two chambers also avoided any significant interaction between change in property and change in member sizes (LeVan et al 1996).

Previous studies of wood durability under cyclic temperatures have often involved relatively short cycles of about 24 h (Moore 1983; LeVan et al 1996). Depending upon the specimen size, this has sometimes resulted in the heating and cooling periods being a significant proportion of the exposure period, which can make interpretation of the contribution of these periods to overall degradation more complicated (see permanent effects for a variable temperature in the Discussion section).

To avoid this, we chose a heating period of 30 da followed by removal to a room maintained at room temperature for another 30 da. So at the end of the first 30-da exposure period, all lumber in the cyclic portion of the study was put on carts and moved to the room temperature chamber where it was again placed on stickers between each row of 2×4's. Thirty days later the lumber was moved back to the 82°C chamber and placed on stickers.

Following final conditioning at room temperature and 20% RH, the E_{TV} of the lumber was determined. The lumber was then taken in sealed tubes to the test floor and tested in ¼-point loading with a span-to-depth ratio of 21:1 following procedures of ASTM D 198 (2006). In the winter, the RH in the building was near that of the final conditioning room, but for lumber to be tested in the summer, the use of the sealed tubes helped to assure that it did not pick up excessive moisture prior to test. The rate of loading was approximately 50 mm/min. Following testing, specimens were cut from the middle of the 2×4 near failure for determination of moisture content (ASTM D 4442, 2006) and specific gravity (ASTM D 2395, 2006). These cross-sectional specimens were about 25-mm long. A similar specimen was cut for chemical analysis and ground to pass 30-mesh screen. Hemicellulose content was determined from wood flour following the procedures of Pettersen and Schwandt (1991) and is more thoroughly discussed in Green et al (2003, 2005). Acidity was determined using a pH meter in a water and wood-flour solution.

RESULTS

Table 2 summaries the flexural properties of three grades of lumber tested in this study. Here the specimens that were subjected to cyclic exposure are shown with the total elapsed time since the start of the experiment. The time they were at 82°C was one-half of this time. As has been reported previously, there is little effect of temperature on the MOE of solid-sawn 2×4's, and therefore no consistent difference between the MOE obtained after continuous or cyclic exposure (Green et al 2003, 2005).

Residual MOR

The residual MOR value is the mean MOR after a given exposure period divided by the mean value of the unexposed control group. Residual MOR values are given in Table 3. Here the exposure period of the specimens subjected to cyclic exposure is given as the period of time the specimens were at 82°C and 30% RH (therefore one-half of the total time). These values are plotted in Figs 2–4. For ease of comparison, a solid line has been drawn between the data points for continuously-exposed specimens, but not for the data points for the cyclic specimens. In all instances, the residual MOR value of the cyclic specimens is less than that found, or expected from interpolation, from specimens showing continuous exposure. For the 2250f-grade southern pine, the cyclic specimens are 2.8% less than the expected value for the continuously-exposed specimens that we obtained by linear interpolation between the data points at 10 and 20 mo. For 2700f southern pine, the residual MOR of the cyclic specimens is 3.2–5.4% less than that of the continuous exposure groups, and for Select Structural Douglas-fir it is 5.2–12.2% less. For all three species-grade combinations, the largest percentage difference between the residual MOR of the continuous and cyclic exposure groups occurs at the longest exposure time.

The significance of the differences between the continuous and cyclic residuals was evaluated two ways: 1) a statistical analysis was conducted of differences in data trends with time of exposure for the cyclic vs continuously-exposed groups, and 2) the efficiency with which E_{TV} predicted mean MOR of untreated control groups was used to judge practical differences

TABLE 3. *Residual MOR of solid-sawn lumber exposed continuously or intermittently at 82°C, 30% RH for various periods and tested at room temperature at about 4% moisture content.*

		Continuous		Intermittent	
Species	Grade	Exposure (mo)	Residual MOR	Exposure[1] (mo)	Residual MOR
Southern pine	2250f	0	1.000	0	1.000
		10	0.643	5	—
		20	0.588	10	—
		30	0.550	15	0.587
Southern pine	2700f	0	1.000	0	1.000
		10	0.717	5	0.827
		20	0.604	10	0.673
		30	0.548	15	0.606
Douglas-fir	Sel.Str.	0	1.000	0	1.000
		10	0.814	5	0.855
		20	0.759	10	0.721
		30	0.602	15	0.664

[1] Intermittent exposure assumed to be ½ of actual elapsed time.

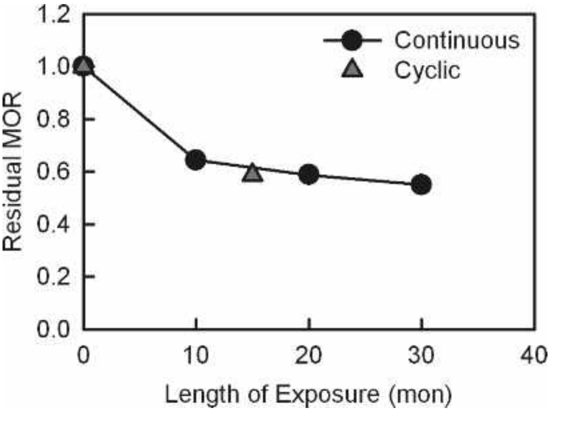

FIGURE 2. Residual MOR of 2250f-1.9E southern pine 2×4's after continuous and cyclic exposure at 82°C, 30% RH.

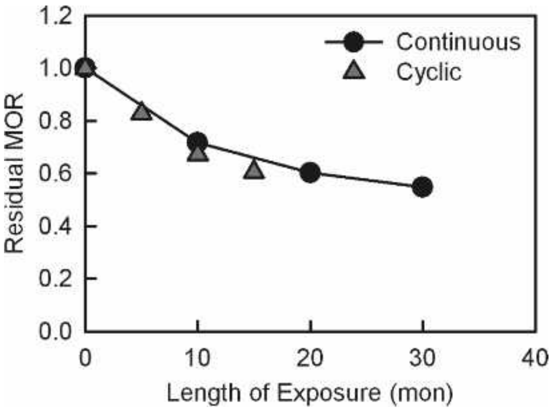

FIGURE 3. Residual MOR of 2700f-2.2E southern pine 2×4's after continuous and cyclic exposure at 82°C, 30% RH.

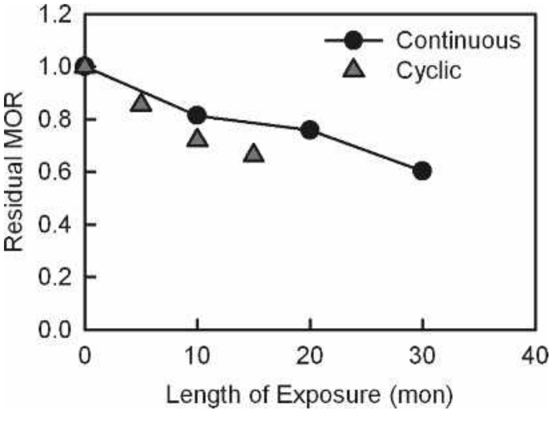

FIGURE 4. Residual MOR of Select Structural Douglas-fir 2×4's after continuous and cyclic exposure at 82°C, 30% RH.

between the MOR of cyclic and continuously-exposed groups at a given time.

In the first approach, a statistical analysis was conducted of the difference between the regression lines of residual MOR vs the logarithm of exposure time. For specimens that were continuously exposed, there was no difference between the regression lines for the three species-grade combinations at the 0.05 confidence level ($F = 2.617$, $F_{0.05} = 5.91$). There was also no difference at the 0.05-level between the three combinations that were exposed in the cyclic phase ($F = 2.856$, $F_{0.05} = 6.39$). With no difference between species-grade combinations, we then merged the three sets for each type of exposure. Separate regression lines were then fit to the cyclic exposure data, and to the continuously-exposed data. These regressions were not significantly different at the 0.05 confidence level ($F = 4.518$, $F_{0.05} = 19.45$).

A second approach used the efficiency with which we could predict the mean MOR of untreated specimens using our E_{TV} based matching procedure as an indication of the practical effect of cyclic vs continuous exposure. As previously noted, our unexposed control group for each species-grade combination was composed of two subsets that had been sorted using the E_{TV} ranking procedure (Table 4). With perfect matching, both subsets of the control groups should have equal values of MOR. We then calculated a percentage difference by dividing the difference between the means by the average of the means for each species-grade combination. For the unexposed southern pine 2250f-lumber the difference in MOR values is 3.3%; for the 2700f southern pine it is 4.0%; and for the visually-graded Douglas-fir the difference is 12.5% (Table 5).

We then estimated the percentage differences between the residual MOR values measured for the cyclic-exposure groups with the values found for continuous exposure. When the exposure time for the cyclic-exposure groups fell between the equivalent times for continuous exposure, we interpolated from a straight line between measured points for the continuous-exposure specimens. These differences are also shown in Table 5. For 2250f southern pine, the

TABLE 4. *Comparison of matching for control groups.*[1]

Species	Grade	N	MC (%)	Mean E_{TV}	Mean MOR
Southern pine	2250f-1.9E	30	4.0	17.85	87.22
		60	4.2	19.08	90.75
Southern pine	2700f-2.2E	30	4.6	16.08	74.92
		29	4.6	16.62	72.46
Douglas-fir	Sel.Str.	30	5.5	12.23	57.03
		31	5.2	13.51	50.31

[1] See footnote for table 2

TABLE 5. *Comparison of difference in residual MOR values between cyclic and continuous exposure groups with the percent difference of the subgroups of the control specimens.*

Species	Grade	Equivalent[1] Exposure (mo)	Difference[2] (%)
Southern pine	2250f-1.9E	0	4.0
		15	2.8
Southern pine	2700f-2.2E	0	3.3
		5	3.2
		10	4.4
		15	5.4
Douglas-fir	Sel.Str.	0	12.5
		5	5.2
		10	9.3
		15	12.2

[1] Cyclic exposure is given as one-half total elapsed time.
[2] Difference for 0-time exposure is the % difference calculated from the mean MOR values of the two control group subsets given in Table 4.
Difference for the other exposure groups is the residual of the cyclic group minus the residual of the equivalent continuous exposure specimens, Table 2.

difference between the cyclic and continuous residuals is 2.8% at a cumulative exposure of 15 mo for the cyclic specimens. Because this value is less that the 4% difference we found between the two matched subsets of the control specimens, we conclude that the 2.8% reduction for the cyclic specimens is not significantly different than that of the control specimens. For the 2700f southern pine MSR, the percentage difference after 15 mo of cumulative exposure is 5.4%. This is slightly greater than the 3.3% difference we could estimate for the control specimens of this species-grade combination. The largest difference for the visually-graded Douglas-fir is 12.2% after 15 mo of equivalent cyclic exposure. This seems a much greater difference than found for the southern pine. However, the properties of visually-graded lumber are more variable than those of MSR, and the difference after 15 mo is still slightly less that the difference of 12.5% that we obtained for the two Douglas-fir control subsets. Overall, we conclude that there is no difference between the residual MOR of the cyclic specimens and those that had continuous exposure.

Both approaches to evaluating residual MOR values for 2×4's support the historical assumption that repeated (ie cyclic) exposure to elevated temperature over prolonged periods has a cumulative effect on wood properties that can be estimated by summing up the effects for the intermediate high temperature exposure periods. While the difference in residual MOR between those specimens that saw cyclic exposure and those that saw continuous exposure, are judged to be not different over the 30 mo of exposure, it is noted that the difference is increasing with length of exposure. It was observed that checking and warp seemed greater for the cycled specimens than for the continuously-exposed specimens. Perhaps cyclic thermal stresses are causing this slightly greater loss over time than was observed with the continuously-exposed specimens. If this hypothesis is correct, a conservative estimate might be considered for members subjected to large and rapid thermal swings.

Change in chemical composition

Previous studies have shown that hemicelluloses, especially arabinose, are sensitive to thermal degradation (Fengel and Wegener 1984; LeVan et al 1990; Winandy 1995; Green et al 2003, 2005). Table 6 gives the acidity and hemicellulose content of the lumber tested in this study. As previously discussed, the exposure times of the 2×4's in the cyclic temperature portion of the study are shown in Table 6 as the total elapsed time. For this lumber, the equivalent period of exposure at 82°C would be one-half of this period. As expected, the wood generally becomes more acidic (pH decreases) with length of exposure. Of the hemicelluloses measured, only arabinose shows a consistent reduction with period of exposure. In Figs 5–7, we plot the residual arabinose content vs exposure time. As was done with residual MOR, a solid-line is shown between data points for the continuously-exposed specimens, and the data points for cyclic exposure are plotted for the equivalent period of time they were actually exposed at 82°C (one-half of the total exposure time for our study). The cyclic data points fit nicely with the continuous data. This supports the historical decision to evaluate intermittent exposure based on a summation of time periods at an elevated temperature and our conclusions based on residual

TABLE 6. *Hemicellulose content solid-sawn 2×4's exposed at 82°C and 30% RH and tested at room temperature and 20% RH.*

Species	Grade	Exposure[a] (mo)	Hemicellulose (% of dry weight)					pH
			Arabinose	Galactose	Xylose	Mannose	Glucose	
Continuous Exposure								
Southern pine	2250f-1.9E	0	1.01	1.62	5.51	12.40	43.8	4.2
		10	0.54	2.31	5.33	11.96	43.0	3.6
		20	0.35	2.34	5.16	11.64	43.7	—
		30	0.26	2.79	4.74	11.20	41.5	3.3
Southern pine	2700f-2.2E	0	0.97	3.82	5.83	10.02	41.8	4.5
		10	0.54	2.31	5.33	11.96	43.0	3.6
		20	0.32	2.33	5.22	11.50	42.1	—
		30	0.28	4.01	5.67	9.33	40.0	3.3
Douglas-fir	Sel. Str.	0	1.14	3.57	4.07	13.03	42.5	3.8
		10	0.76	4.15	3.61	12.30	42.2	3.4
		20	0.71	4.15	4.00	12.48	42.1	—
		30	0.60	2.91	4.07	13.20	43.1	3.1
Cyclic Exposure								
Southern pine	2250f-1.9E	0	1.01	1.62	5.51	12.40	43.8	4.2
		30	0.42	4.23	5.15	10.25	38.5	3.6
Southern pine	2700f-2.2E	0	0.97	3.82	5.83	10.02	41.8	4.5
		10	0.67	2.27	6.56	10.49	41.8	3.8
		20	0.49	1.91	5.86	11.42	43.8	—
		30	0.40	3.90	5.58	10.10	39.8	3.4
Douglas-fir	Sel. Str.	0	1.14	3.57	4.07	13.03	42.5	3.8
		10	0.86	3.71	4.05	13.00	42.3	3.7
		20	0.86	5.09	4.24	12.18	41.6	—
		30	0.77	4.47	4.28	11.85	41.1	3.1

[a] Cumulative length of exposure at 82°C for the Cyclic exposure groups is half of the period shown.

MOR values. Had the cyclic points been plotted at the total elapsed time, they would have consistently indicated higher residual values.

DISCUSSION

Estimating strength loss in the real world usually requires engineering judgment in combining research recommendations with actual exposure conditions. The results presented in this paper are for lumber that is continuously dry, but exposed to high temperatures over long periods of time. While this is probably the more common situation where members are exposed to high temperatures over long time periods, there are instances where both the RH and temperature may vary (Powell 1982). Time and resources did not permit us to study the effect of cyclic temperatures at high RH levels or combinations of high and low RH levels. Thus, we have not confirmed the historical recommendation that cyclic effects are additive for the latter exposure situations.

Permanent effects for a variable temperature

Our cyclic temperature regime was designed to test the historical recommendations given in the Wood Handbook for summing temperature exposures while avoiding some of the experimental problems that can plague temperature experiments (Moore 1983; LeVan et al 1996). Thus, the cyclic exposure periods were long compared with the time required to heat and cool the lumber. The temperature cycle shown in Fig 1 is one real-world type exposure. How can we estimate the residual MOR for this cyclic exposure? Summing the continuous exposure at 90°C over the actual, or expected, life of the structure is fairly straight-forward. However, the additional effect of the cooling period requires judgment. As a

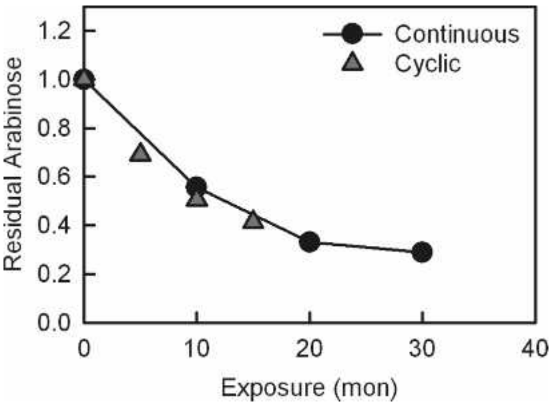

FIGURE 5. Residual arabinose content of 2700f-2.2E southern pine 2×4's after continuous and cyclic exposure at 82°C, 30% RH.

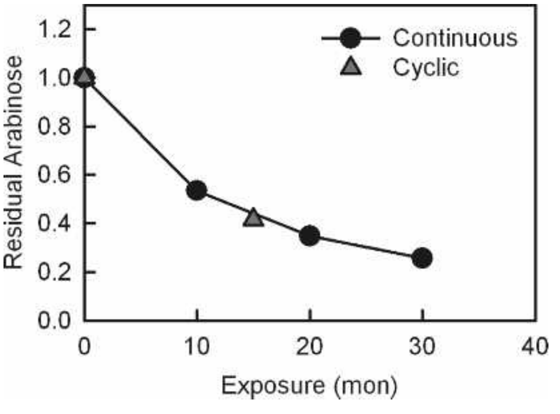

FIGURE 6. Residual arabinose content of 2250f-1.9E southern pine 2×4's after continuous and cyclic exposure at 82°C, 30% RH.

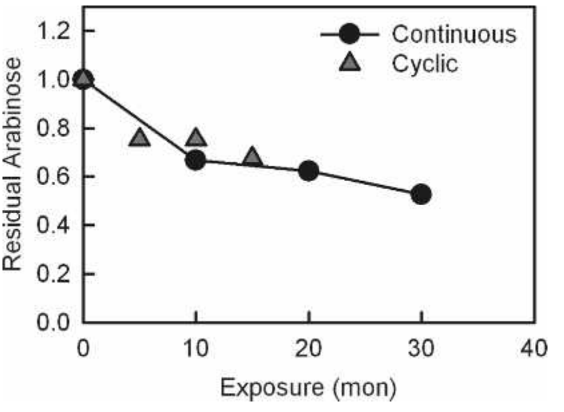

FIGURE 7. Residual arabinose content of Select Structural 2×4's after continuous and cyclic exposure at 82°C, 30% RH.

simplistic "first pass," let us assume the 12-h cooling period from hours 8–20 was approximated by a triangular area with a straight hypotenuse that had a base equal to 12 h and a height of 70°C above room temperature. The centroid of this area would be located at ⅓ the base and ⅓ the height. We might then assume that the cooling period would be equivalent continuous exposure of about 43°C (0.33*70° + 20°) for an additional 4 h. This equivalent exposure would then be summed over 8 mo to compare with a 2-yr continuous exposure. None of our earlier data suggests that there would be any significant thermal additional thermal degradation at 43°C after only 8 mo continuous exposure. Even at 66°C and 25% RH, there is only about a 7% loss in MOR after a 12-mo continuous exposure (Green et al 2003).

In the simplistic example shown above we have ignored the fact that once acids have been generated as a result of thermal degradation at 90°C, they are still present during the cooling-down period and might hasten additional degradation. And the triangulation assumption we used to estimate thermal equivalency is extremely simplistic. But the conclusion we reached is that the chance of additional degradation is probably not detectible for that temperature and short time-frame. Had the results suggested the possibility of additional degradation, we could have used more realistic assumptions to estimate additional degradation. This analysis also supports Moore's revised observation that his 8 mo of continuous exposure is equivalent to 2 yr of cyclic exposure, and our observation that there is no difference in his residual MOR when we compare his results after 8 mo of continuous exposure to that after 2 yr cyclic exposure.

Estimating total effects

The permanent property losses discussed here are based on tests conducted after the specimens were cooled to room temperature in a chamber

TABLE 7. *Estimation of total loss in MOR for lumber tested hot after 3 yr of continuous exposure at 66°C at 75% RH (Green et al 2003).*

Product	Species	Grade	Estimated Loss (%)			Measured Total Loss (%)
			Reversible	Permanent	Total	
Solid-sawn	SPF	1650f-1.5E	13	33	46	44
Solid-sawn	SPF	2100f-1.8E	17	27	44	38
LVL	Douglas-fir	2.0E	12	35	47	43
LVL	Southern pine	2.0E	12	32	44	45
LVL	Yellow poplar	2.0E	18	35	53	55

that would result in no change in moisture content. Historically it has been recommended that if the specimens are tested hot after long-term temperature exposure, the percentage of strength reduction would be based on the combination of the reduction for the immediate effect of temperature plus the permanent effect (FPL 1999). This recommendation has been confirmed for 2×4's of solid-sawn lumber and LVL exposed for 3 yr at 66°C and 75% RH (Green et al 2003). In that study, some lumber was tested at 66°C after only a short period (48 h) of exposure (immediate effect), some tested at room temperature after 3-yr exposure (permanent effect), and some tested at 66°C after 3-yr exposure (total effect). Although specimen sizes for the solid-sawn lumber were only approximately 30 pieces per lumber species and 15 per LVL species, the precision of the estimation of total loss by summing the losses for the immediate and permanent effects is remarkably good (Table 7). An alternative approach based on the product of the residual MOR values (Winandy and Rowell 2005) was found to give essentially equivalent results (Green et al 2005). Because this is a more severe exposure, these results would almost assuredly apply had the RH level been lower.

Limitations on the use of the results of this study

As previously indicated, this study is part of a larger program to evaluate the permanent effects of temperature on the properties of structural lumber products. Some of the experimental results from the larger study have been published (Green et al 2003, 2005). However a paper summarizing all the results for lumber exposed at low RH over long periods is still in progress. This study is narrowly focused on how to relate data obtained during cyclic exposure at low RH levels to data obtained for continuous exposure. The data presented here for continuous exposure represent only a small portion of the data that will be included in the future paper. An additional paper is also in progress to present analytical models that could be used to estimate times to specified residual MOR levels for a wide range of product types, species, grades, RH levels, and temperatures. The limited data presented here are not adequate for this purpose. Finally, material performance is only one aspect that must be considered in engineering design. Making structural design recommendations requires input from experts from many fields. In the United States, such concerns are usually done through consensus organizations such as the American Society for Testing in Materials, and the technical committees of the American Forest and Paper Association that input into the National Design Specification.

CONCLUSIONS

Based on our results on solid-sawn 2×4's exposed at 82°C and 30% RH for up to 30 mo we conclude that:

1. There is no significant difference in the residual MOR obtained when the lumber is cycled between the higher temperature and room temperature at constant moisture content compared with that of lumber exposed continuously for an equivalent time.
2. The traditional recommendation given in the

Wood Handbook that repeated exposure to elevated temperatures has a cumulative effect on strength properties gave a conservative estimate of residual MOR compared with the results from continuous exposure.

3. The reduction in arabinose content with cyclic exposure is approximately equal to that found for continuously-exposed specimens for an equivalent duration of continuous exposure.

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