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Evaluation of a Boron-Nitrogen, Phosphate-Free Fire-Retardant Treatment. Part II. Testing of Small Clear Specimens per ASTM Standard D 5664-95, Methods A and B*

ABSTRACT: The objective of this work was to evaluate the effects of a new boron-nitrogen, phosphate-free fire-retardant (FR) formulation on several mechanical properties of FR-treated wood and to assess the potential of this treatment for in-service thermal-induced strength loss resulting from exposure to high temperature. Fire-retardant-treated and untreated small clear specimens were cut from three wood species, Douglas-fir, southern pine, and white spruce, according to ASTM D 5664-95 and evaluated in bending and tension. compression, and shear parallel to grain. Evaluations were conducted before and after matched specimens were exposed at elevated temperature (150°F (66°C)) for 36, 72, or 108 days. The results indicate that treatment with FR and redrying followed by long-term exposure at high temperature could significantly affect some mechanical properties when compared to the same properties of untreated and unexposed controls. However, FR treatment and redrying in themselves did not have an across-the-board effect on all properties of specimens or on the rate of strength loss compared to the properties of matched untreated lumber exposed at 150°F (66°C) for up to 108 days. Our analysis indicated that for some species. some engineering properties will require modification, whereas other species-property combinations will not. Our results indicate that the likelihood of FR-treated lumber to experience in-service reduction in mechanical properties when exposed to elevated temperatures is no different than that of matched untreated material.

KEYWORDS: lumber, roof truss, thermal degradation, fire-retardant treatment

This is the second report in a three-part series on the effects of a new boron-nitrogen. phosphate-free fire-retardant (FR) treatment on wood strength and strength retention at high temperature. Part I reports results from tests on Douglas-fir plywood in accordance with ASTM D 5516-96. Part II, reported here, describes results from tests on nominal 2- by 4-in. (standard 38- by 89-mm) (hereafter called 2 by 4) Douglas-fir, southern pine. and spruce lumber, performed in accordance with Methods A and B of ASTM D 5664-95. Part III reports results from tests on 2 by 4 southern pine lumber as specified in Method C of ASTM D 5664-95.

In the work reported here: small clear specimens were cut from 2 by 4 Douglas-fir. southern pine. and white spruce lumber according to Method A of ASTM D 5664-95 [1]. These were used to evaluate the initial effect of boron-nitrogen, phosphate-free FR treatment and redrying on bending properties and shear, compression, and tension parallel-to-grain strength. In Method B, additional small clear specimens were cut from 2 by 4 Douglas-fir, southern pine, and white spruce lumber that had been exposed for 36, 72, or 108 days at 150°F (66°C). These were used to evaluate the potential for thermal degradation of the new FR and consequent effects on bending properties and shear, compression. and tension parallel-to-grain strength.

The Forest Products Laboratory (FPL) was interested in performing the work reported here for two reasons. First: to date, no one has published data obtained using the procedures described in the currently approved version of ASTM Standard D 5664-95 [1]. The D 5664 standard evolved after several iterations from nonstandardized test methods originally and arbitrarily developed as building product evaluation criteria by code bodies or industrial associations. Although the evaluation criteria of the current ASTM D 5664 standard are similar to those of the original-version, they are certainly not identical to the original criteria used to qualify current commercially available FR formulations. The data and experience gained from this work may be used to develop an understanding of the attainable precision and bias of ASTM Standard D 5664 or to improve its design or economy. Second, when this work began, no phosphate-free FR formulation existed in the commercial market. Our research may have direct benefits to consumers with respect to safety and long-term serviceability if the new phosphate-free FR is eventually accepted by national building codes and standardized through the American Wood Preservers' Association (AWPA).

Objectives

The overall objectives of this three-phase program were: (a) to evaluate the effect of a new boron-nitrogen, phosphate-free FR formulation on several mechanical properties and for several types of material. and (b) to evaluate the potential for wood treated with this new FR to experience in-service reductions in mechanical properties when exposed to elevated temperatures when compared to the same mechanical properties of matched untreated material. The ob-

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jective of the work reported here (Phase II) was to evaluate the initial effects of treatment and redrying and the potential for long-term strength effects related to exposure to elevated in-service temperatures using small clear specimens cut from three species of nominal 2 by 4 lumber.

Method and Materials

The material was first evaluated using transverse vibration. Modulus of elasticity (*MOE*) was used as the sorting criterion to match lumber groups. Matched specimens were subjected to FR treatment, redrying, environmental exposure, and mechanical testing. The experimental design (Table 1) consisted of three species (Douglas-fir. southern pine, and white spruce) of nominal 2 by 4 lumber, two treatments (FR-treated and untreated), and two exposure conditions (no exposure or exposure for 36, 72, or 108 days at 150°F (66°C) and 75% RH). After exposure, the full-size 2 by 4 lumber was cut into small clear specimens and destructively tested in bending or in shear, compression, or tension parallel to grain. The results were analyzed to determine the initial effect of treatment and redrying on these mechanical properties and the potential for thermal-induced loss in properties when exposed to elevated in-service temperatures.

Material

The study material consisted of 8-ft (2.4-m)-long 2 by 4 lumber The lumber was purchased in the highest grade obtainable in which we could be assured of single species groups More specimens were obtained for Douglas-fir and white spruce than for southern pine because of their refractory nature Douglas-fir lumber was obtained from a mill in the western Cascade region of Oregon and graded as 2400f-2.0E MSR. Southern pine lumber was obtained from a mill in southwestern Arkansas and graded as No. 1 & better The white spruce required for testing by ASTM D 5664 was difficult to obtain This standard requires white spruce, but this species is not graded or sold commercially as a single species group To obtain a single species allotment of white spruce, we obtained construction grade lumber from a mill in the Prince George region of British Columbia, Canada, which processes nearly 100% white spruce in their Spruce-Pine-Fir species group.

TABLE 1 —*Experimental design for bending and shear, compression and tension parallel-to-grain tests.* [a]

		Number of Specimens for Various Exposure Times (days) at 150°F (66°C) and 75% RH[b]			
Species	Treatment	0	36	72	108
Southern pine	Untreated	30	30	30	30
	FR-treated	30	30	30	30
Douglas-fir	Untreated	30	30	30	30
	FR-treated	30	30	30	30
White spruce	Untreated	25	25	25	25
	FR-treated	25	25	25	25

[a] Methods A and B of ASTM D 5664.

[b] For groups of 30 specimens, each 8-ft (2.4-m) long 2 by 4 was cut into two sections 4-ft (1.2-m) long. One section was assigned to the treated group, the other to the untreated group. Groups of 25 specimens were parsed from original 32-specimen groups after treatment to eliminate specimens that did not comply with retention requirements. RH is relative humidity.

Specimen Sorting

Modulus of elasticity was determined on the basis of the transverse vibration and dimensions of each piece of lumber. These *MOE* values were then used as a sorting variable to assign the 8-ft (2.4-m) long 2 by 4s into *MOE*-matched groups for Douglas-fir. southern pine, and white spruce (Table 1). This *MOE*-based sorting technique was used because it helped ensure that. for all three species evaluated. each group had nearly identical distributions of high, middle. and low stiffness specimens. Such a technique helps ensure that any post-experimental difference in properties is directly attributable to the experimental variables and not to chance variation.

We evaluated 144 pieces of 2400f-2.0E Douglas-fir lumber. To reduce variability, pieces with the 16 highest and 8 lowest MOE values were culled. The remaining 120 pieces were then sorted into four *MOE*-matched groups of 30 pieces each (Table 1). Southern pine (120 pieces) was likewise sorted into four MOE-matched groups of 30 pieces each (Table 1). The white spruce sample consisted of 292 pieces of lumber. To reduce variability related to the diverse quality levels allowed in construction-grade Spruce-Pine-Fir, pieces with the 68 highest and 96 lowest *MOE* values were culled in an effort to produce uniform *MOE* in the remaining 128 pieces, which were then sorted into four *MOE*-matched groups of' 32 pieces each. After treatment, these groups were further culled to 25 pieces each to further eliminate treatment variability.

For all three species. each 8-ft (2.4-m)-long 2 by 4 was cut into two end-matched 4-ft (1.2-m)-long sections. One section was assigned to the FR-treated group. the other to its exposure-matched untreated group (Table 1). Thus. small clear specimens cut from the 4-ft (1.2-m)-long lumber were matched by *MOE* across exposures and end-matched between treatment across exposures.

Treatment

The FR-treating formulation[3] was supplied by Osmose. Inc.[4] (Buffalo, NY) Prior fire testing had established the minimum chemical retention levels to be used in these experiments for each species to meet the required flame spread and flame progression limits set forth in national building codes and in AWPA Standard C20[2].

We employed a full-cell treatment process including a final vacuum For each species, all four groups of 4-ft (1.2-m)-long specimens were treated at one time An initial vacuum of just over 25 in. Hg (−85 kPa) was held for 45 min. Various concentrations of FR solution in water were then introduced into a 3-ft (0.9-m)-diameter. 10-ft (3-m)-long treating cylinder. solution concentration depended on the results of preliminary treatment trials for each species. Immediately afterward. pressure of 150 lb/in.^{2} (1 MPa) was held for various durations. depending on species (Table 2). The treating solution was drained off at the end of the pressure period, and a final vacuum of just over 25 in Hg (−85 kPa) was held for 10 min.

The average retention of FR chemical (as opposed to solution) for the 120 unincised Douglas-fir specimens was 1 .67 lb/ft^3 (267

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[3] Fire-retardant formulation used as described in U.S. Patent No. 6.306.317 it has recently been introduced in U.S. Markets as “FirePRO™”.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service. Osmose, Inc. is not associated with the Federal Government government. The information given in this section and this should not be construed as any endorsement or approval of the chemical or processes reported.

TABLE 2—*Treating data for 4-ft (1.2-m)-long Douglas-fir, southern pine, and white spruce 2 by 4 lumber.* [a]

								Chemical Retention					
				Gain		Gross Absorption		First		Second		Total	
Species	n	Pressure Duration, (Min)	Solution Concentration, (%)	(g)	(lb)	(kg/m^3)	(lb/ft^3)	(lb/ft^3)	(kg/m^3)	(lb/ft^3)	(kg/m^3)	(lb/ft^3)	(kg/m^3)
Douglas-fir[b]	120	180 (1st)	12.5	871	1.92	213	13.15	1.60	25.6	1.22	19.5	2.82	45.1
		360 (2nd)	12.5	(290)	(0.64)	(71)	(4.38)	(0.53)	(8.5)	(0.80)	(12.8)	(0.84)	(13.4)
Southern pine	120	90	7.0	253	5.58	621	38.28	2.68	42.9	...	...	...	...
				(162)	(0.36)	(40)	(2.45)	(0.17)	(2.7)	...	...	...	...
White spruce	100	180	16.0	867	1.91	213	13.12	2.10	33.6				
				(425)	(0.94)	(104)	(6.43)	(1.03)	(16.5)	...	...	...	...

[a] Data reported are average values. Values in parentheses are standard deviation.

[b] Douglas-fir was treated twice: first, for 180 min, yielding retention of 1.60 lb/ft^3 (25.6 kg/m^3); second. for 360 min, adding retention of 1.22 lb/ft^3 (19.5 kg/m^3). Total retention is the sum (2.82 lb/ft^3 (45.1 kg/m^3)) of these two treatments.

TABLE 3—*Post-treatment kiln drying schedule for FR-treated 2 by 4 lumber.*

Time. h	Dry-Bulb Temp., °F (°C),	Wet-Bulb Temp. °F(°C)	Wet-Bulb Depression. °F(°C)	RH, %	EMC,[a] %
0–4	130(54)	Vent	NA	NA	NA
4–24	130(54)	115 (46)	15 (8.3)	62	9.7
24–48	150(66)	125 (52)	25 (13.9)	48	6.9
48–72	160(66)	130 (54)	30 (16.7)	43	5.8
72–120	Slowly cooled to 95°F (35°C) over weekend		43–50	6–10	

[a] EMC is equilibrium moisture content

kg/m^3). Thirty-two specimens exceeded the Underwriters Laboratory (UL) specified retention required for a FR-S flame-spread rating. The remaining 88 under-treated Douglas-fir specimens were air dried to <25% moisture content and retreated using the same schedule. Combining the gross retentions of the first and second treatments, the average retention for the 120 Douglas-fir specimens was 2.82 lb/ft^3 (45.1 kg/m^3). The processing details, solution concentration, and general summary of absorption and retention are given in Table 2. The average FR retention for the 120 southern pine specimens was 2.68 lb/ft^3 (42.9 kg/m^3). and the average retention for the 128 white spruce specimens was 1.99 lb/ft^3 (31.8 kg/m^3).

Based on treating characteristics. 100 white spruce specimens were selected for further study. For these specimens. average retention was 2.10 lb/ft^3 (33.6 kg/m^3). All these specimens exceeded the UL-specified retentions required for a Class A flame-spread rating. To ensure that the culling process for nonconforming treatment had not affected the original MOE matching. the remaining 100 treated white spruce specimens were resorted, along with the matched untreated specimens. into four new pretreatment *MOE*-matched groups of 25 specimens each. End matching between FR-treated and untreated material was retained.

Redrying

All FR-treated 2 by 4 lumber specimens were kiln dried after treatment using a 2000 board-foot (15.6-m^3) steam-heated brick kiln. Osmose, Inc. provided a post-treatment kiln-drying schedule (Table 3) applicable to relatively small volumes of lumber in experimental-sized kilns and within the temperature limitations of AWPA Standard C20. Throughout the four kiln-drying stages, an average constant air speed of 200 to 220 ft/min (65 to 70 m/min) was maintained through the load with fan reversal every 3 h. The first two stages were intended to facilitate heat absorption by the wood. The latter two stages facilitated drying. The maximum kiln temperature of 160°F (71°C) was achieved in 48 to 72 h into the kiln-drying process. The final 48 h involved turning the kiln off, but keeping the doors shut, vents closed, and fans slowly running for a slow ramp-down of kiln temperature over a weekend. Total time in the kiln was 120 h, with a final kiln temperature of 95°F (35°C). Lumber moisture content was initially 30 to 125% and finally approximately 12 to 21%. While the selected drying schedule was appropriate for small kiln loads. different schedules using similar maximum temperature limits will be needed for commercial kilns.

After redrying, all specimens (both untreated and FR-treated) were conditioned to constant weight at 74°F (23°C) and 65% RH, which generally results in about 12% moisture content in untreated wood

High Temperature Exposure

After conditioning to constant weight at 12% moisture content, each 4-ft (1.2-m)- long 2 by 4 specimen intended for either the 36-. 72-. or 108-day high-temperature exposure was exposed at 150°F (66°C) and 75% RH for the assigned time. After the appropriate exposure period was completed, all 4-ft (1.2-m)-long specimens (both untreated and FR-treated, exposed and unexposed) were reconditioned to constant weight at 74°F (23°C) and 65% RH

Small Clear Specimens

After conditioning to constant weight, each FR-treated and untreated 2 by 4 was cut into small clear specimens as described in ASTM D 5664 [1]. Care was taken to avoid cutting specimens with strength—reducing characteristics, such as knots, cross grain,, or slope-of—grain excess of 1 in 12. Because of the propensity for many small knots in white spruce, priority for obtaining perfectly clear, knot-free specimens for property tests was given in the following order: tension. shear, compression, and bending specimens. Particularly for white spruce, it was nearly impossible to obtain perfectly clear bending specimens. Thus, some very small knots of less than 0.1 in. (2.5 mm) in diameter were occasionally present in some specimens. When cutting small specimens, one wide surface was not machined. Each specimen was later tested so that this surface was exposed to greater stress during the particular mechanical test, because the unmachined face should have the highest FR retention and should present a worst-case scenario with respect to treatment effects. In an attempt to extend usable material because of problems posed by knots and grain deviations. only one tension parallel-to-grain specimen was cut and tested from each 4-ft (1.2-m)-long section. In addition, the specific gravity/moisture content block was cut from the bending specimen after it had been tested.

Mechanical Testing

Each small clear specimen was tested in bending or in shear: compression, or tension parallel to grain as appropriate. All specimen sizes and testing conditions were as described in ASTM D 5664. For each test. load was measured with a calibrated load cell. Both the load cell and a linear variable differential transducer (LVDT) were interfaced to a computer that recorded load and the property being tested. For bending tests, the rate of loading caused failure in 1 to 3 min. For the other tests, the rate of loading caused failure in 3 to 5 min.

For bending tests, the test span was 22 in. (559 mm) and the rate of loading was 0.5 in. (12.5 mm)/min. Centerpoint deflection was measured using an LVDT mounted on a yoke suspended from pins located at the neutral axis above the reaction supports. Modulus of elasticity (*MOE*), modulus of rupture (*MOR*), maximum load capacity (P_{max}). and work to maximum load (*WML*) were measured. After each bending test, a 3-in. (76-mm)-long section was cut from near the point of failure to calculate specific gravity and moisture content at time of test.

For tension parallel-to-grain tests; special grips were used that proportionally tightened their pressure as load increased. These grips lessened or precluded perpendicular-to-grain crushing at the grips from interfering with the test (ASTM D 143) [3]. The rate of loading was 0.035 in. (0.89 mm)/min, and the load cell determined ultimate tensile stress (*UTS*).

For compression parallel-to-grain tests, a steel orbital load head was used to avoid eccentricities in the plane of load application resulting from slight differences between the plane of the load head and that of the specimen (ASTM D 143). The rate of loading was 0.018 in. (0.46 mm)/min, and maximum crushing strength (*MCS*) was calculated.

For shear tests, a steel block-shear test fixture (ASTM D 143) with a shear face offset of 0.125 in. (3.18 mm) was used to avoid crushing stresses across the shear plane. The rate of loading was 0.024 in. (0.6 mm)/min, and shear strength was calculated.

Analysis

Data analysis took into account the *MOE* of the original 8-ft (2.4-m)-long 2 by 4 lumber, which was obtained by transverse vibration. The tests of significance were obtained using analysis of covariance techniques employing the original transverse-vibrational *MOE* as the covariable. For each mechanical property, parameter estimates of the initial property and the rate of property change were developed for each group. Then. two pretest comparisons were run for each property. In the first comparison; we evaluated and tested the significance of the initial effect of treatment and redrying on lumber properties. In the second comparison. we evaluated and tested the significance of any difference in the rate of property loss over duration of high-temperature exposure. Considering the matched sample size required in Methods A and B of ASTM D 5664 (25 to 30 specimens). we employed a 95% level of significance as our criterion for practical significance.

Results

In a few cases. mechanical property data were missing. In some cases, data were excluded from analysis when some unforeseen defect was noticed in the small clear specimen after it was destructively tested. In other cases, the location of knots or grain deviation in the 4-ft (1.2-m)-long 2 by 4 lumber precluded the cutting of a particular small clear specimen. This minor loss of data should not in any way influence the practical interpretation of the experimental data.

For each species, specific gravity and moisture content at time of test are given in Table 4. For each mechanical property evaluated, the number of specimens tested, mean value, and standard deviation are

TABLE 4—*Specific gravity and average moisture content of small clear specimens tested by ASTM D 5664-95 Methods A and B*

Treatment	Days at 150°F (66°C)	Douglas-fir *n*	Douglas-fir Mean	Douglas-fir SD	Southern Pine *n*	Southern Pine Mean	Southern Pine SD	White Spruce *n*	White Spruce Mean	White Spruce SD
					SPECIFIC GRAVITY					
Untreated	0	30	0.52	0.05	30	0.54	0.04	25	0.43	0.03
	36	30	0.50	0.03	30	0.52	0.05	25	0.44	0.03
	72	30	0.51	0.05	30	0.52	0.04	25	0.43	0.03
	108	30	0.51	0.04	30	0.52	0.04	25	0.43	0.02
FR- treated	0	28	0.53	0.05	30	0.54	0.04	25	0.45	0.04
	36	30	0.51	0.04	30	0.52	0.04	25	0.45	0.03
	72	30	0.52	0.05	30	0.52	0.03	25	0.43	0.03
	108	30	0.51	0.04	30	0.52	0.03	25	0.44	0.03
					MOISTURE CONTENT, %					
Untreated	0	30	12.4	0.6	30	12.2	0.9	25	11.5	0.8
	36	30	12.7	0.5	30	13.2	0.4	25	13.0	0.4
	72	30	11.8	0.3	30	12.3	0.3	25	12.1	0.3
	108	30	12.2	0.3	30	12.2	0.3	25	12.4	0.2
FR-treated	0	28	13.2	1.0	30	14.5	0.4	25	12.1	1.1
	36	30	13.8	0.8	30	15.0	0.3	25	13.9	0.7
	72	30	12.9	0.5	30	13.6	0.3	25	13.1	0.4
	108	30	13.3	0.4	30	13.6	0.4	25	13.3	0.5

TABLE 5*a—Properties of FR-treated and end-matched untreated small clear specimens—S1 units.*

Property [a]	Treatment	Days at 66°C	Douglas-fir			Southern Pine			White Spruce		
			n	Mean	SD	*n*	Mean	SD	*n*	Mean	SD
MOE (Gpa)	Untreated	0	30	14.4	1.9	30	12.7	1.9	25	11.2	1.4
		36	30	14.3	1.4	30	12.5	1.9	25	10.6	1.2
		72	30	14.6	1.8	30	12.7	2.3	25	10.8	1.0
		108	30	15.1	1.8	30	12.8	1.6	25	11.1	1.0
	FR-treated	0	28	14.5	1.8	30	11.9	1.4	25	11.1	1.9
		36	30	14.5	1.6	30	12.4	2.0	25	10.6	1.2
		72	30	15.3	1.4	30	12.3	1.6	25	10.3	1.3
		108	30	15.2	1.9	30	12.8	1.8	25	11.2	1.0
MOR (MPa)	Untreated	0	30	87.0	15.1	30	91.3	12.3	25	69.7	11.1
		36	30	89.4	8.7	30	86.1	10.9	25	70.8	9.3
		72	30	96.1	12.8	30	91.4	12.8	25	76.9	8.3
		108	30	96.7	11.6	28	86.9	13.8	25	72.7	7.5
	FR-treated	0	28	85.5	16.5	30	79.1	10.9	25	60.0	15.7
		36	30	88.7	11.9	30	77.5	13.1	25	65.5	10.8
		72	30	98.2	13.1	30	82.I	8.1	25	65.7	12.5
		108	30	98.3	13.8	30	81.9	10.6	24	70.2	10.4
WML (kJ/m^3)	Untreated	0	30	68.3	26.I	30	78.8	31.7	25	46.7	19.1
		36	30	66.2	16.3	30	67.2	15.1	25	53.0	16.3
		72	30	71.8	28.5	30	64.7	24.8	25	54.2	14.7
		108	30	75.4	26.1	28	52.4	18.5	25	44.8	13.6
	FR-treated	0	28	48.5	21.5	30	44.6	20.2	25	28.5	15.4
		36	30	54.1	20.0	30	43.1	19.4	25	37.7	17.0
		72	30	62.1	21.9	30	41.4	11.7	25	32.1	12.3
		108	30	62.5	25.6	30	38.0	12.3	24	36.0	15.0
UTS (MPa)	Untreated	0	25	112.7	35.9	29	116.7	32.1	22	93.4	28.9
		36	26	111.1	36.1	27	113.8	26.1	23	99.8	18.6
		72	26	105.4	33.6	26	121.4	20.9	23	88.2	24.7
		108	22	105.7	26.4	29	107.4	29.1	20	89.5	23.0
	FR-treated	0	26	95.2	25.8	28	103.9	27.4	22	92.8	35.2
		36	26	108.5	33.0	30	95.3	27.1	23	89.8	26.0
		72	29	100.5	33.9	30	96.1	32.7	22	88.5	23.7
		108	18	93.5	35.4	28	89.5	18.4	23	79.9	30.2
MCS (MPa)	Untreated	0	30	47.4	6.1	30	50.2	5.0	25	38.7	4.7
		36	30	50.5	5.5	29	49.0	5.3	25	41.4	3.4
		72	30	52.9	7.9	30	48.5	5.6	25	39.9	5.0
		108	30	51.1	5.2	30	47.8	4.6	25	39.3	4.7
	FR-treated	0	27	58.7	4.8	30	49.3	5.3	25	43.2	4.2
		36	30	56.3	5.2	30	47.3	5.7	24	41.4	4.5
		72	30	59.4	8.6	30	50.1	4.1	25	42.8	5.4
		108	30	54.1	6.6	30	49.4	5.1	24	40.4	4.8
Shear (MPa)	Untreated	0	30	12.4	1.7	30	12.4	1.2	25	9.9	1.4
		36	30	11.0	1.2	30	12.0	1.5	25	10.5	1.1
		72	30	10.1	1.9	30	12.3	1.4	25	11.9	1.6
		108	30	10.7	1.9	30	11.2	1.3	25	12.1	1.7
	FR-treated	0	27	11.9	1.5	29	12.3	1.6	25	10.0	1.6
		36	30	11.2	1.7	30	11.4	1.5	25	10.1	1.5
		72	29	10.4	1.4	30	12.3	1.4	25	12.0	2.1
		108	30	10.2	1.4	29	11.1	1.4	24	10.8	1.4

[a] MOE is modulus of elasticity; MOR, modulus of rupture: WML, work to maximum load; UTS, ultimate tensile strength; MCS, maximum compressive strength

given in Table 5. For each species, the FR-treated and untreated groups were compared using a parameter termed the ratio of effect, i.e., the change in the property compared to that of matched untreated and unexposed specimens. Ratios of effect are given for the initial effect and overextended durations of high- temperature exposure. Thesecomparisons are shown for *MOE, MOR, WML, UTS, MCS,* and shear in Figs. 1 to 6, respectively. The results of these tests indicate important differences between FR-treated and untreated material.

Discussion

The following discussion focuses on the effects of treatment and extended exposure to elevated temperatures on several properties *(MOE, MOR, WML, UTS, MCS,* and shear) specified as critical in ASTM D 5516 for lumber in service.

Modulus of Elasticity

The MOE of small clear specimens of Douglas-fir and white spruce was initially unaffected by FR treatment and redrying (Table 5, Fig. 1). Initial *MOE* of southern pine was decreased significantly (a £ 0.05) by about 7%. However, in Part III of this research program, full-size 2 by 4 southern pine lumber showed no significant (a £ 0.05) decrease in *MOE* as a result of FR treatment and redrying. In fact, *MOE* of this lumber actually increased slightly. Thus, it might be overly conservative to recommend the

TABLE 5*b—Properties of FR-treated and end-matched untreated small clear specimens—inch-pound units.*

			Douglas-fir			Southern Pine			White Spruce		
Property[a]	Treatment	Days at 150°F	*n*	Mean	SD	*n*	Mean	SD	*n*	Mean	SD
MOE (× 10^6 lb/in.^{2})	Untreated	0	30	2.09	0.28	30	1.84	0.28	25	1.62	0.20
		36	30	2.08	0.20	30	1.81	0.27	25	1.54	0.17
		72	30	2.12	0.26	30	1.84	0.33	25	1.57	0.15
		108	30	2.19	0.26	30	I.85	0.23	25	1.61	0.15
	FR-treated	0	28	2.10	0.26	30	1.72	0.20	25	1.61	0.27
		36	30	2.1I	0.23	30	1.80	0.29	25	1.54	0.17
		72	30	2.22	0.20	30	1.79	0.23	25	1.50	0.19
		108	30	2.2I	0.28	30	1.86	0.26	25	1.62	0.15
MOR (× 10^3 lb/in^2)	Untreated	0	30	12.6	2.2	30	13.2	1.8	25	10.1	1.6
		36	30	13.0	1.3	30	12.5	1.6	25	10.3	1.3
		72	30	13.9	1.9	30	13.2	19	25	11.2	1.2
		108	30	14.0	1.7	28	12.6	2.0	25	10.5	1.1
	FR-treated	0	28	12.4	2.4	30	11.5	1.6	25	8.7	2.3
		36	30	12.9	1.7	30	11.2	1.9	25	9.5	1.6
		72	30	14.2	1.9	30	11.9	1.2	25	9.5	1.8
		108	30	14.3	2.0	30	11.9	1.5	24	10.2	1.5
WML (in·lb/in^3)	Untreated	0	30	9.91	3.79	30	11.43	4.60	25	6.78	2.77
		36	30	9.60	2.36	30	9.74	3.64	25	7.69	2.37
		72	30	10.42	4.14	30	9.38	3.59	25	7.86	2.13
		108	30	10.93	3.78	28	7.60	2.68	25	6.50	1.97
	FR-treated	0	28	7.04	3.12	30	6.47	2.93	25	4.13	2.24
		36	30	7.85	2.90	30	6.25	2.82	25	5.47	2.47
		72	30	9.00	3.18	30	6.00	1.70	25	4.65	1.79
		108	30	9.07	3.72	30	5.51	1.78	24	5.22	2.17
UTS (× 10^3 lb/in^2)	Untreated	0	25	16.3	5.2	29	16.9	4.7	22	13.5	4.2
		36	26	16.1	5.2	27	16.5	3.8	23	14.5	2.7
		72	26	15.3	4.9	26	17.6	3.0	23	12.8	3.6
		108	22	15.3	3.8	29	15.6	4.2	20	13.0	3.3
	FR-treated	0	26	13.8	3.7	28	15.1	4.0	22	13.5	5.1
		36	26	15.7	4.8	30	13.8	3.9	23	13.0	3.8
		72	29	14.6	4.9	30	13.9	47	22	12.8	3.4
		108	18	13.6	5.1	28	13.0	2.7	23	11.7	4.4
MCS (× 10^3 lb/in.^{2})	Untreated	0	30	6.9	0.9	30	7.3	0.7	25	5.6	0.7
		36	30	7.3	0.8	29	7.1	0.8	25	6.0	0.5
		72	30	7.7	1.1	30	7.0	0.8	25	5.8	0.7
		108	30	7.4	0.8	30	6.9	0.7	25	5.7	0.7
	FR-treated	0	27	8.5	0.7	30	7.2	0.8	25	6.3	0.6
		36	30	8.2	0.8	30	6.9	0.8	24	6.0	0.7
		72	30	8.6	1.3	30	7.3	0.6	25	6.2	0.8
		108	30	7.8	1.0	30	7.2	0.7	24	5.9	0.7
Shear (× 10^3 ib/in.^{2})	Untreated	0	30	1.8	0.2	30	1.8	0.2	25	1.4	0.2
		36	30	1.6	0.2	30	1.7	0.2	25	1.5	0.2
		72	30	1.5	0.3	30	1.8	0.2	25	1.7	0.2
		108	30	1.6	0.3	30	1.6	0.2	25	1.7	0.3
	FR-treated	0	27	1.7	0.2	29	1.8	0.2	25	1.5	0.2
		36	30	1.6	0.2	30	1.6	0.2	25	1.5	0.2
		72	29	1.5	0.2	30	1.8	0.2	25	1.7	0.3
		108	30	1.5	0.2	29	1.6	0.2	24	1.6	0.2

[a] *MOE* is modulus of elasticity, MOR, modulus of rupture, *WML*, work to maximum load; *UTS*, ultimate tensile strength. *MCS*, maximum compressive strength

use of a modification factor for *MOE* of southern pine on the sole basis of the results from tests on small clear specimens.

For all three species, there was no significant difference between FR-treated and untreated material in the trend in *MOE* on extended exposure at 150°F (66°C) for up to 108 days (Fig. 1). Thus, no adjustment to *MOE* with respect to in-service thermal loading appears necessary.

Modulus of Rupture

Modulus of rupture of small clear Douglas-fir specimens was initially unaffected by FR treatment and redrying (Table 5, Fig. 2). Initial *MOR* of southern pine and white spruce was decreased significantly (a £ 0.05) by about 14%. It might be appropriate to use a similar modification factor as an adjustment to allowable design stress values for bending strength of southern pine and white spruce.

No significant difference between FR-treated and untreated Douglas-fir and white spruce occurred in *MOR* on extended exposure at 150°F (66°C) for up to 108 days. Although southern pine showed an initial difference between FR-treated and untreated material, this difference has little practical implication for extended exposure because the trends in *MOR* converge (Fig. 2). Thus, no adjustment with respect to in-service thermal loading appears necessary for the bending strength of any of the three wood species under consideration.

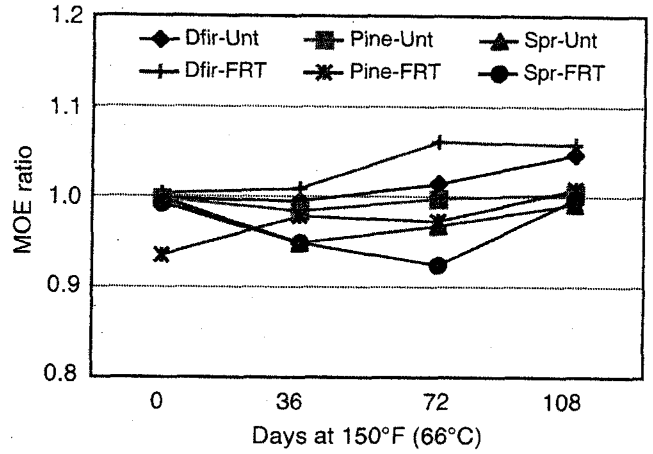

FIG. 1—*Effects of fire-retardant (FR) treatment and exposure at 150°F (66°C) on MOE of small clear specimens. Dfir is Douglas-fir; Pine, southern pine; Spr, white spruce, Unt, untreated: FRT, FR-treated.*

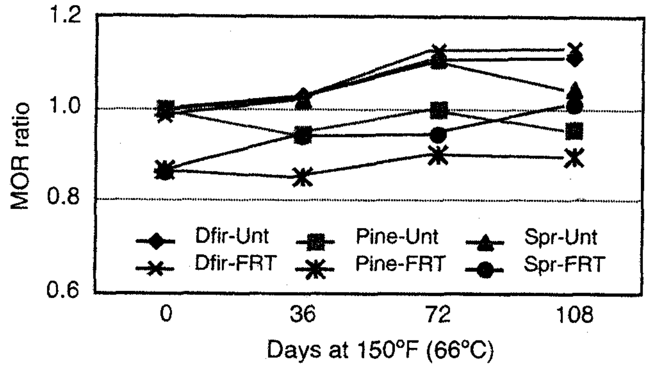

FIG. 2—*Effects of FR treatment and exposure at 150°F (66°C) on MOR of small clear specimens*

Work to Maximum Load

Fire-retardant treatment and redrying significantly (a £ 0.05) decreased the initial *WML* for Douglas-fir, southern pine, and white spruce by about 29, 43, and 39%, respectively (Table- 5, Fig. 3). Work to maximum of load is a measure of energy absorption, and materials exhibiting reduced energy absorption are generally less ductile. Thus, for lumber, as for other treated wood products (both preservative- and FR-treated), it would be prudent to not apply an impact loading adjustment to the duration-of-load adjustment (C_d) and to limit C_d to the wind/earthquake adjustment (i.e., C_d £ 1.6).

For Douglas-fir and white spruce, there was no significant difference between FR-treated and untreated material in trend in WML on extended exposure at 150°F (66°C) for up to 108 days (Fig. 3). For southern pine, a significant (a £ 0.05) difference between FR-treated and untreated material occurred after extended exposure. However, similar to the results noted with *MOR* of southern pine, these trends in *WML* between FR-treated and untreated lumber converged (Fig. 3). As such, no further adjustment with respect to in-service thermal loading appears necessary for energy-related properties.

Ultimate Tensile Strength

The initial *UTS* of small clear specimens of Douglas-fir was decreased by about 15% by FR treatment and redrying (Table 5, Fig. 4). but this difference was not significant at a £ 0.05 (actual level of significance £ 0.13). The initial *UTS* of southern pine was decreased significantly (a £ 0.05) by about 11% by FR treatment and redrying. The initial *UTS* of white spruce was initially unaffected by FR treatment and redrying. It might be appropriate to use a modification factor of about 10% as an adjustment to allowable design stress values for tensile strength of Douglas-fir and southern pine.

For all three species, no significant difference in *UTS* trend between FR-treated and untreated material occurred on extended exposure at 150°F (66°C) for up to 108 days. However, from a practical viewpoint. the difference in *UTS* between FR-treated and untreated specimens after 108 days was an additional 5% for southern pine and 10% for white spruce (Fig. 4). As such, if a design modification factor of 10 to 15% for tensile strength was conservatively applied to account for the initial effect of treatment and redrying for all three wood species tested, then no further adjustment with respect to in-service thermal loading would appear necessary.

Muximum Crushing Strength

Initial *MCS* of small clear specimens of FR-treated Douglas-fir and white spruce was increased significantly (a £ 0.05) by about 24 and 11%. respectively (Table 5, Fig. 5). Initial *MCS* of southern pine was unaffected by FR treatment and redrying. Consequently,

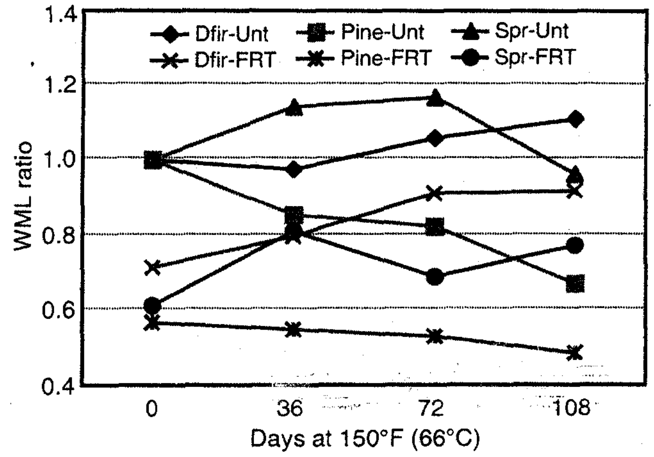

FIG 3—*Effects of FR treatment and exposure at 150°F (66°C) on WML of small clear specimens.*

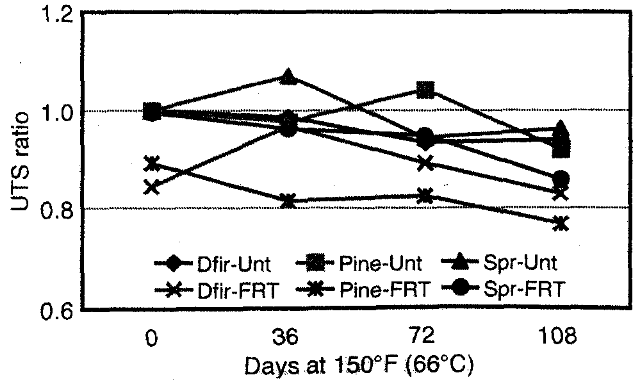

FIG 4—*Effects of FR treatment and exposure at 150°F (66°C) on UTS of small clear specimens.*

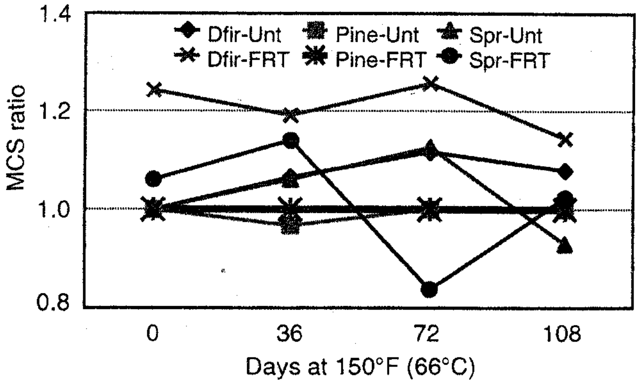

FIG. 5—*Effects of FR treatment and exposure at 150°F (66°C) on MCS of small clear specimens.*

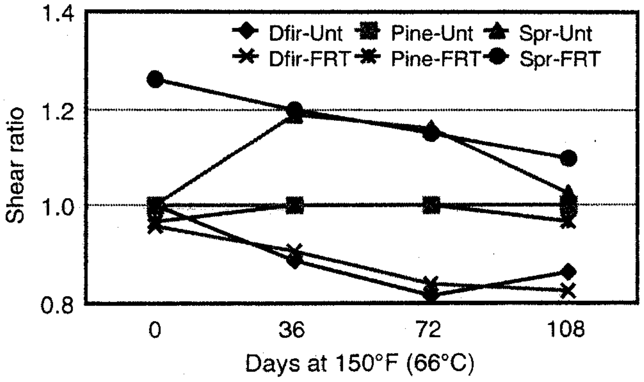

FIG. 6—*Effects of FR treatment and exposure at 150°F 166°C) on shear strength of small clear specimens.*

no adjustment to the design values for *MCS* (i.e., compression strength parallel to grain) apparently is needed

Douglas-fir and southern pine showed no significant difference between FR-treated and untreated material in *MCS* trend on extended exposure at 150°F (66°C) for up to 108 days For white spruce, a discernable difference between FR-treated and untreated material occurred on extended exposure, bur the *MCS* trends of FR-treated and untreated material converged (Fig 5) As such, no adjustment with respect to in-service thermal loading appears necessary for *MCS*

Shear Strength

The shear parallel-to-grain strength of small clear specimens of Douglas-fir, southern pine, and white spruce was initially unaffected by FR treatment and redrying (Table 5, Fig. 6). No adjustment to shear strength design values is apparently needed.

There was also no significant difference between FR-treated and untreated material in the trend in shear strength on extended exposure at 150°F (66°C) for up to 108 days (Fig. 6). As such, no adjustment appears to be needed for shear strength design values with respect to in-service thermal loading.

Conclusions

The data and trends reported in this paper are indicative of results expected from FR-treatment retentions and post-treatment kiln temperatures similar to those evaluated in this three-phase evaluation of a boron-nitrogen, phosphate-free FR treatment. Our analysis indicates that for some species, some engineering properties will require modification; other species-property combinations will not require modification. Modulus of elasticity *(MOE),* maximum crushing strength (*MCS*), and shear properties were the least affected by FR treatment and redrying. Thus, no adjustment for an initial treatment effect for these properties would appear necessary. Generally, modulus of rupture (*MOR*) and ultimate tensile stress (*UTS*) were decreased significantly (a £ 0.05) by treatment and redrying (10 to 15%). However. such effects for boron-nitrogen, phosphate-free FR are less than those associated with other commercially available FR formulations and only about half that allowed under AWPA Standard C20 Section 4.1 requirements [4]. Work to maximum load (*WML)* of all three wood species was decreased significantly, by 30 to 45%. This finding is similar to previous findings with current commercial FR formulations. As with all other preservative and FR treatments. it would be prudent to prohibit the application of the impact load adjustment for duration-of-load and limit C_d £ 1.6.

For extended exposure of lumber to elevated temperatures while in service, our analysis showed no consistent indication or potential for boron-nitrogen, phosphate-free FR-treated lumber to experience in-service reductions in mechanical properties when exposed to elevated temperatures at any differential rate than that of matched untreated 2 by 4 lumber.

Recommendations For Modifications to ASTM D 5664-95

After conducting this series of tests. we question the need to test all three species (Douglas-fir, southern pine. and white spruce) when using ASTM D 5564. No critical information or engineering insight was acquired from the white spruce data that was not noted from the southern pine or Douglas-fir results. Thus, we think a third species should be optional. It was impossible to find very high grade white spruce. and it was nearly impossible to cut small clear specimens from the lower grades of white spruce that were available commercially. Therefore. we suggest that if ASTM Subcommittee D07.07 still believes that a third species group is necessary. the D 5664-95 standard should be modified to require a commercially available wood species, such as red maple and or yellow poplar, or a commercial species group, such as Hem-Fir or Spruce-Pine-Fir.

References

[1] ASTM D 5664-95: Standard Test Method for Evaluating the Effects of Fire-Retardant Treatments and Elevated Temperatures on the Strength Properties of FRT Lumber, *Annual Book of ASTM Standards*, Vol. 4.10, ASTM International, West Conshohocken, PA, 1998.

[2] AWPA Standard C20-98: Structural Lumber—Fire-Retardant Treatment by Pressure Processes, *AWPA Annual Book of Standards*, American Wood Preservers' Association, Granbury, TX, 2000, pp. 100–101.

[3] ASTM D 143: Standard Test Method for Evaluating the Mechanical Properties of Timber Using Small, Clear Specimens, *Annual Book of ASTM Standards*, Vol. 4.10, ASTM, West Conshohocken, PA, 1998.

[4] AWPA Standard C20-00: Lumber Fire-Retardant Treatment by Pressure Processes, *AWPA Annual Book of Standards*, American Wood Preservers' Association, Granbury, TX, 2000.