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# Effects of Fire Retardant Treatments After 18 Months of Exposure at 150°F (66°C)

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## Abstract

In some situations, fire-retardant-treated plywood roof sheathing and roof truss lumber have experienced strength loss from thermal degradation. The combination of elevated temperatures on roof systems, fire retardant chemicals, and moisture may prematurely activate the fire retardant. Previous studies examined the physical, mechanical, and chemical properties of fire-retardant-treated wood at various temperatures over a short period. In this study, we examined the rate of strength loss at elevated temperature over a long duration. Small, clear Southern Pine specimens treated with six different fire retardant chemicals were exposed at 150°F (66°C)/75 percent relative humidity for up to 18 months. The results, consistent with those of previous studies, clearly show that the phenomenon of fire-retardant-related thermal degrade is systematic and potentially quantitative. The results also support the hypothesis that the lower the pH of the fire-retardant-treated wood and/or the dissociation energy of the treatment in the wood, the higher the rate of strength loss over time.

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# Effects of Fire Retardant Treatments After 18 Months of Exposure at 150°F (66°C)

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## Introduction

Field problems of reduced strength capacity have developed in some situations where material treated with fire retardant (FR) is exposed to elevated temperatures (APA 1989, LeVan and Collet 1989, NAHB 1990). In many cases, roofs made with FR-treated material have required replacement. In these cases, the wood was darkened in color, was brittle, crumbled easily, and exhibited excessive cross-grain checking. For the severely degraded roofs, service time has ranged from 1 to 8 years (APA 1989, NAHB 1990).

The effects of FR treatments and the mechanism suspected to cause thermal-related failure were described previously (LeVan and Winandy 1990). Past research showed that the magnitude of wood degradation depends on the FR formulation (LeVan et al. 1990), exposure temperature and relative humidity (Winandy et al. 1991), construction details that dictate roof temperatures (Heyer 1963, Rose 1992), and ventilation, which, together with construction details, dictates wood moisture content in roof systems (Rose 1992).

Studies at the Forest Products Laboratory have focused on physical, mechanical, and chemical properties of matched specimens exposed at different temperatures and relative humidity levels in an effort to evaluate the rate of strength loss over time at elevated temperature. Results of exposure tests at 80°F (27°C), 130°F (54°C), and 180°F (82°C) were not conclusive as to whether the relationship between strength loss and temperature/duration of exposure is linear or nonlinear (LeVan et al. 1990, Winandy et al. 1991). This was in part due to the shortness of the exposures—only 160 days. Here we present the results of exposure of FR-treated wood to 150°F (66°C)/75 percent relative humidity (RH) for up to 18 months.

## Experimental Methods

### Materials

Small, clear, 5/8-in.- (16-mm-) tangential by 1-3/8-in.- (35-mm-) radial by 12-in.- (305-mm-) long bending test specimens were cut from nominal 1-in.- (standard 19-mm-) thick vertical-grain Southern Pine lumber. Specimens were sorted according to modulus of elasticity (MOE) using nondestructive stress-wave techniques. The sort resulted in 161 MOE- and density-matched groups of 30 specimens each. The average stress-wave MOE value for each group was  $2.12 \times 10^6$  lb/in<sup>2</sup> (14.6 GPa), with a coefficient of variation of 14 percent. Stress-wave MOE values ranged from  $1.5$  to  $2.7 \times 10^6$  lb/in<sup>2</sup> (10.3 to 18.6 GPa). Results of tests on 84 matched groups exposed at various temperatures and for various durations were reported by LeVan et al. (1990) (Table 1). Here, we report the results of another matched set of 42 groups exposed at 150°F (66°C) (Table 1). The 150°F (66°C) exposures were performed approximately 1 to 2 years after the 130°F (54°C) and 180°F (82°C) exposures.

**Table 1—Environmental exposure conditions and duration**

Exposure temperature (°F) <sup>a</sup>	Relative humidity (percent)	Equilibrium moisture content (percent)	Duration (days)	Study
80	30	6	3, 160	LeVan et al. 1990
130	73	12	3, 7, 21, 60, 160	LeVan et al. 1990
150	75	12	7, 21, 60, 160, 290, 560	Present report
180	50	6	3, 7, 21, 60, 160	LeVan et al. 1990

$${}^aT_C = (T_F - 32) (0.56).$$

**Table 2—Chemical retention levels and pH**

Chemical	Average retention		Concentration (% wt)	Solution		
	(lb/ft <sup>3</sup> )	(kg/m <sup>3</sup> )		Pre-treatment pH	Post-treatment pH	Dissociation constant <sup>a</sup> K <sub>a</sub>
Phosphoric acid (PA)	3.64	58.2	8.38	1.43	1.30	7.5 x 10 <sup>-3</sup>
Monoammonium phosphate (MAP)	3.47	55.5	8.14	4.27	4.21	1.6 x 10 <sup>-7</sup>
Borax/boric acid (BBA)	3.52	56.3	8.14	7.96	8.06	5.8 x 10 <sup>-10</sup>
Guanylurea phosphate/boric acid (GUP/B)	3.47	55.5	8.19	3.10	3.13	7.9 x 10 <sup>-8</sup>
Dicyandiamide formaldehyde (DEF)	3.55	56.8	8.24	3.75	3.75	—
Diethyl-N,N-bis (2-hydroxyethyl) aminomethyl phosphonate (OPE)	3.46	55.4	8.14	6.58	5.46	—

<sup>a</sup>Zumdahl 1989.

Specimens were treated with six FR chemicals (Table 2). Specimens were impregnated using a full-cell pressure process with a gauge vacuum of 30 inHg (−101 kPa) for 30 min and a pressure of 150 lb/in<sup>2</sup> (1.03 MPa) for 60 min. Concentration of the chemical solutions was adjusted to give approximately 3.5 lb/ft<sup>3</sup> (56 kg/m<sup>3</sup>) retention (Table 2). To minimize premature drying after treatment, specimens were bundled in polyethylene and stored in a 36°F (2°C) cold room until all specimens could be dried at once. All FR-treated specimens were then kiln-dried at a dry-bulb temperature of 110°F (43°C) and a wet-bulb temperature of 100°F (38°C) for 9 days, followed by 7 days at 120°F (49°C) and a wet-bulb temperature of 112°F (44°C) to a final moisture content of 12 percent.

## Procedures

Specimens were exposed in an environmental chamber at 150°F (66°C) and 75 percent RH for durations up to 18 months. Prior to testing, all specimens were reequilibrated to constant weight at 74°F (23°C) and 65 percent RH.

Specimens were tested in flat-wise bending with a span of 9 in. (22.9 mm), center-point loading, and a loading rate of 0.19 in/min (4.8 mm/min). The length, width, thickness, and weight of each specimen were measured prior to testing. Load–deflection data were continuously monitored and recorded. From this information, static MOE, modulus of rupture (MOR), and work to maximum load (WML) were calculated. After mechanical testing, moisture content (ASTM 1994a) and density (ASTM 1994b) were measured for each piece.

After static bending tests, a small section from each specimen was cut near the failure point. These sections were ground to 40 mesh (approximately 372  $\mu\text{m}$ ) in a Wiley mill. A mixed representative sample of each chemical/exposure/duration group was subjected to chemical analysis. Analyses of sugar, acid-soluble lignin, and Klason lignin content were conducted generally following the procedures of Pettersen and Schwandt (1991), Tappi Method 250 (1992), and Effland (1977), respectively.

## Results and Discussion

The post-exposure moisture content and specific gravity for each group exposed at 150°F (66°C) and reequilibrated to constant weight at 74°F (23°C) and 65 percent RH are given in Table 3. Note that the reported equilibrated moisture content for the 7-day-exposure specimens was 1 to 3 percent lower than would be expected at 74°F (23°C) and 65 percent RH. A recheck of the data indicated that the moisture content of all specimens exposed for 7 days was nearly the same as that of the specimens exposed for 21, 60, 160, 290, or 560 days. We cannot explain the apparently low moisture content of the 7-day specimens; we had never witnessed this phenomenon in previous studies. We think that this group of material may have been improperly conditioned, but have been unable to confirm that suspicion. The effects of exposure on mechanical properties (MOE, MOR, and WML) are given in Table 4.

### Strength Effects

Results from previous work (LeVan et al. 1990) indicated that 180°F (82°C) exposures produce little practical reduction in MOE, but a considerable loss in strength and energy-related properties (i.e., WML). The 80°F (27°C) exposures also had no effect on strength or WML, and the 130°F (54°C) exposures produced relatively little change in MOR or WML after 160 days of exposure. For the 150°F (66°C) exposures, WML was the mechanical property most sensitive to the influence of chemical/exposure/duration effects (Table 4). Because WML is a measure of the ability of a material to absorb energy or to do work (i.e., a force [load] applied over a distance [deflection]), this property is a sensitive indicator of the brittleness of materials. Embrittlement reduces post-elastic plastic deformation and is generally seen as a significantly larger reduction in WML rather than changes in MOE or MOR (Byars and Synder 1975). Furthermore, chemical treatments of wood tend to cause embrittlement. A theoretical explanation for this thermochemical embrittlement will be discussed in the next section on chemical effects.

The results at 150°F (66°C) showed a consistent reduction in bending strength with extended exposure (Fig. 1). These new results, when considered in conjunction with the results of LeVan et al. (1990), showed that for each treatment except BBA, the magnitude and rate of thermal degradation at 150°F (66°C) was consistent with those previously reported strength loss effects at 180°F (82°C) and 130°F (54°C) (Fig. 2). We assumed that the extended storage

**Table 3—Influence of elevated temperature and duration on moisture content and specific gravity of treated and control Southern Pine specimens<sup>a</sup>**

Chemical	Exposure (days)	Moisture content (%)			Specific gravity	
		Mean	Min.	Max.	Mean	SD
UNT	7	9.0	8.2	9.5	0.56	0.04
	21	11.2	10.4	11.7	0.54	0.04
	60	10.8	10.3	11.3	0.56	0.06
	160	10.8	10.1	11.1	0.55	0.04
	290	10.8	10.4	11.1	0.54	0.05
	560	10.7	10.1	11.0	0.53	0.04
PA	7	10.8	9.8	11.6	0.57	0.04
	21	15.7	13.9	18.4	0.52	0.04
	60	16.5	15.1	18.9	0.54	0.04
	160	15.1	13.6	16.6	0.51	0.04
	290	14.6	12.9	16.4	0.51	0.04
	560	16.4	15.0	18.7	0.47	0.03
MAP	7	9.8	9.3	10.1	0.58	0.05
	21	12.7	12.1	13.2	0.56	0.04
	60	11.9	11.1	12.5	0.57	0.04
	160	11.4	10.8	11.9	0.55	0.04
	290	11.9	11.4	12.3	0.54	0.05
	560	13.7	12.9	14.3	0.51	0.05
BBA	7	10.2	9.9	10.6	0.58	0.05
	21	14.4	13.2	14.9	0.55	0.04
	60	13.7	13.2	14.2	0.55	0.04
	160	13.5	13.1	13.9	0.54	0.03
	290	13.4	12.9	14.1	0.54	0.04
	560	12.5	11.7	12.8	0.54	0.04
GUP/B	7	9.2	9.0	9.6	0.57	0.04
	21	12.0	10.6	12.3	0.56	0.04
	60	11.5	11.1	11.7	0.56	0.04
	160	11.0	10.6	11.3	0.57	0.03
	290	10.7	10.5	11.0	0.56	0.04
	560	10.9	10.7	11.2	0.55	0.04
DPF	7	8.5	7.6	8.9	0.59	0.04
	21	11.1	10.9	11.6	0.59	0.03
	60	10.9	10.7	11.2	0.56	0.03
	160	10.8	10.5	11.0	0.58	0.04
	290	10.8	10.5	11.1	0.57	0.04
	560	11.1	10.9	11.4	0.56	0.04
OPE	7	8.5	8.3	8.8	0.57	0.04
	21	10.5	10.2	10.6	0.57	0.04
	60	10.7	10.4	10.9	0.57	0.04
	160	10.8	10.5	11.1	0.57	0.05
	290	10.9	10.5	11.1	0.56	0.04
	560	10.9	10.6	11.2	0.54	0.04

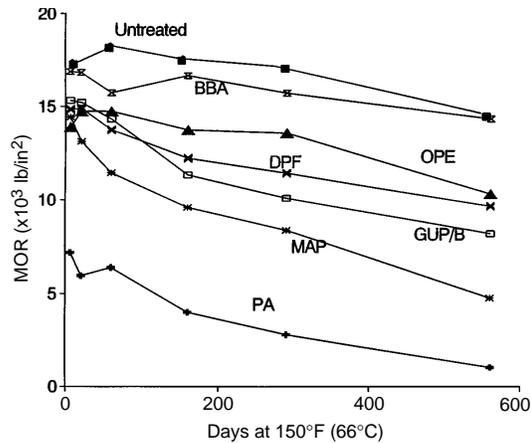
<sup>a</sup>See Table 2 for definition of fire-retardant chemicals. SD is standard deviation; UNT is untreated. All tests were conducted at 150°F (66°C).

**Table 4—Effect of fire retardant on modulus of elasticity, modulus of rupture, and work to maximum load<sup>a,b</sup>**

Chemical	Exposure (days)	MOE ( $\times 10^6$ lb/in <sup>2</sup> )		MOR ( $\times 10^3$ lb/in <sup>2</sup> )		WML (in-lb/in <sup>3</sup> )	
		Mean	SD	Mean	SD	Mean	SD
UNT	7	2.122	0.196	16.814	1.426	13.89	3.24
	21	2.029	0.206	16.513	1.431	14.03	2.97
	60	2.148	0.233	17.730	2.132	14.12	3.50
	160	1.960	0.225	15.823	1.484	11.56	2.47
	290	2.070	0.227	16.448	1.762	10.81	2.09
	560	2.130	0.193	14.002	1.722	7.44	2.70
PA	7	1.712	0.260	7.117	1.872	2.50	1.29
	21	1.474	0.245	5.958	2.020	2.01	1.16
	60	1.526	0.197	6.350	2.091	1.88	1.11
	160	1.191	0.230	3.987	1.333	0.80	0.44
	290	1.012	0.253	2.783	0.620	0.46	0.14
	560	0.477	0.153	0.997	0.288	0.12	0.04
MAP	7	1.937	0.251	14.426	1.950	10.08	2.79
	21	1.782	0.255	13.151	1.435	7.99	2.02
	60	1.862	0.178	11.495	1.671	5.03	1.50
	160	1.697	0.209	9.583	2.465	3.72	1.57
	290	1.693	0.235	8.347	2.198	2.75	1.11
	560	1.521	0.286	4.747	1.506	0.97	0.50
BBA	7	2.000	0.224	16.902	1.929	10.01	2.61
	21	1.901	0.202	16.829	2.265	10.84	3.07
	60	1.901	0.171	15.745	1.759	9.59	2.53
	160	1.938	0.241	16.675	1.762	11.29	2.10
	290	1.927	0.222	15.772	1.710	11.07	2.07
	560	1.945	0.233	14.394	1.849	9.54	2.65
GUP/B	7	2.044	0.235	15.359	1.779	10.71	2.33
	21	1.925	0.225	15.217	1.775	10.52	2.60
	60	1.929	0.257	14.326	2.080	8.34	2.24
	160	1.771	0.142	11.364	1.891	4.87	1.57
	290	1.930	0.224	10.121	2.534	3.57	1.98
	560	1.841	0.307	8.156	1.996	2.44	0.92
DPF	7	1.991	0.222	14.862	1.553	9.41	1.74
	21	1.860	0.217	14.899	1.992	10.14	2.79
	60	1.886	0.259	13.782	2.064	8.07	2.26
	160	1.774	0.187	12.262	1.410	6.12	1.71
	290	1.852	0.191	11.475	2.100	4.93	1.71
	560	1.830	0.248	9.718	2.293	3.66	1.58
OPE	7	1.833	0.252	13.951	2.081	11.33	3.49
	21	1.804	0.220	14.737	1.778	12.32	3.89
	60	1.852	0.220	14.737	1.498	11.20	2.78
	160	1.734	0.188	13.760	1.816	9.44	2.38
	290	1.811	0.232	13.632	2.289	8.37	2.66
	560	1.822	0.209	10.376	2.079	4.66	1.97

<sup>a</sup>All tests were conducted at 150°F (66°C). MOE is modulus of elasticity; MOR, modulus of rupture; and WML, work to maximum load.

<sup>b</sup>1 lb/in<sup>2</sup> = 6.894 kPa; 1 in-lb/in<sup>3</sup> = 82.737 kJ/m<sup>3</sup>.



**Figure 1—Effect of various durations of exposure at 150°F (66°C) on bending strength of untreated and fire-retardant-treated wood.**

of the specimens (1 to 2 years) at 74°F (23°C) prior to exposure had little effect on the results of the 150°F (66°C) exposures for the following reasons:

- the data from the 150°F (66°C) exposures were generally intermediary to the data from the 180°F (82°C) and 130°F (54°C) exposures,
- a statistical test of MOR data from the 7-day exposure period indicated no differences between the 150°F (66°C) and 130°F (54°C) data, and
- the data from the study by LeVan et al. (1990) showed that the ongoing effect of each FR on strength was negligible at 80°F (27°C).

Once degrade had begun at 150°F (66°C), the FR chemicals had a similar rate of strength loss (Fig. 1). This trend was also observed by LeVan et al. (1990). The implication of these findings is that once an elevated temperature has imparted sufficient energy to cause a FR chemical to dissociate into its acidic functional form, the strength degrade rate in any FR-treated wood is similar. Thus, the essential difference between most FR chemical systems is the time and energy required for each chemical to dissociate at a given temperature into its acidic functional form. In the case of each FR evaluated (except BBA) that acidic functional form would be phosphoric acid (H<sub>3</sub>PO<sub>4</sub>). For BBA, that form would be boric acid.

The mechanical property results indicated that qualitatively similar responses occurred in the wood, but we believe that the quantitative differences between the FR chemicals can be explained by two major factors: the initial pH of the FR-treated wood and the potential for that FR to dissociate to its acidic functional form. This potential, as measured by the dissociation constant ( $K_a$ ) (Table 2), dictates the temperature and cumulative exposure time needed for the FR to produce its acid functional unit. The resulting acid then accelerates the thermal degrade process. In general, the influence on strength properties is apparently highly dependent on the initial acidity and on the thermal stability of each FR formulation (Fig. 2). Specifically, the effect of FR chemicals on the strength properties of wood apparently depends on the type of FR chemical and the cumulative temperature exposure level. The phosphoric acid (PA) and monoammonium phosphate (MAP) treatments reduced strength properties most severely (Fig. 1). The other chemical formulations reduced strength properties to a lesser extent.

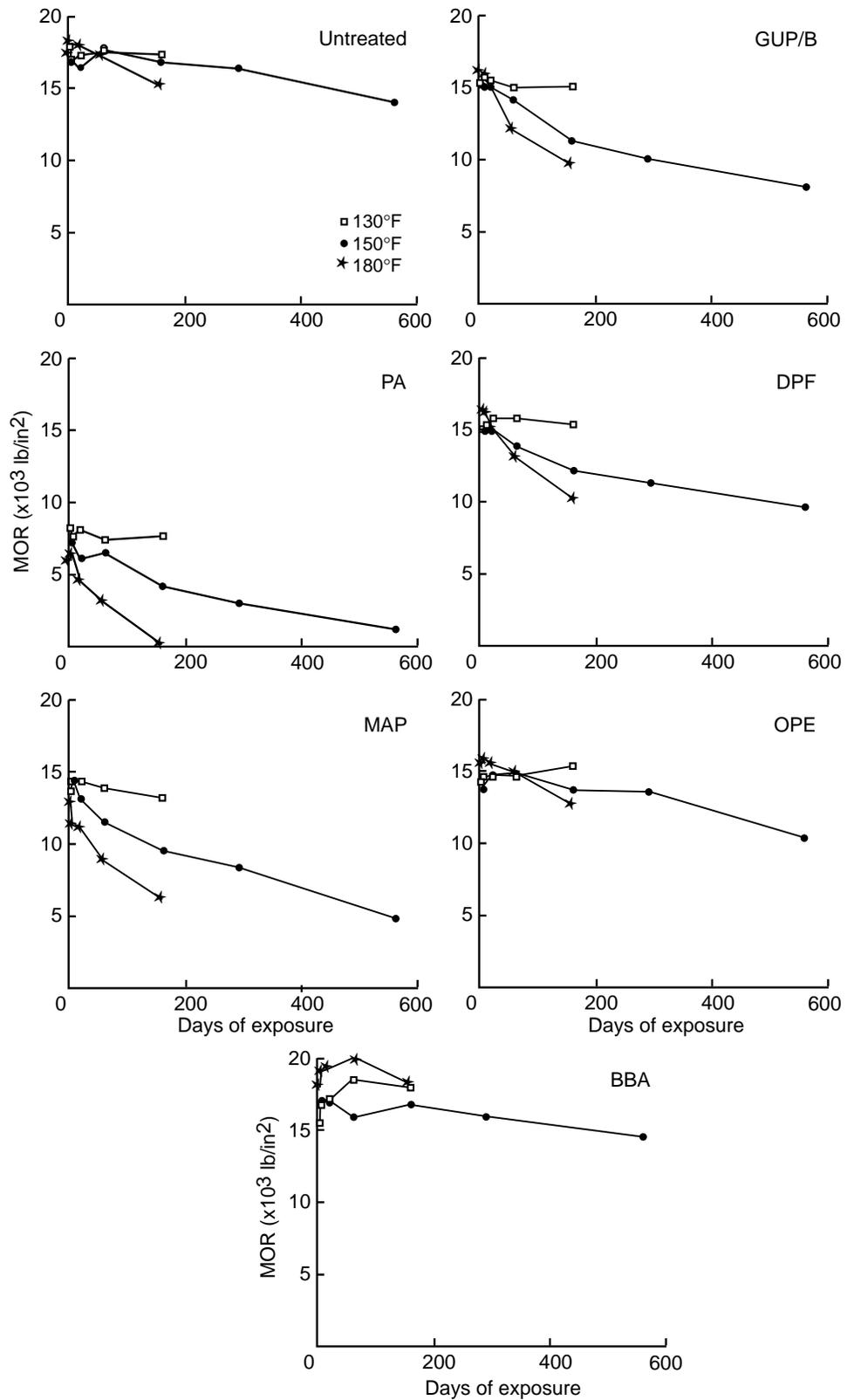


Figure 2—Effect of temperature on bending strength. Data on 150°F (66°C) exposure from study reported here; data on 130°F (54°C) and 180°F (82°C) exposures from study by LeVan et al. (1990). Untreated, phosphoric acid (PA), monoammonium phosphate (MAP), guanylurea phosphate (GUP/B), dicyandiamide–phosphoric acid–formaldehyde (DPF), organophosphate ester (OPE), and borax–boric acid (BBA).

The consistency in the magnitude of the effects of FR treatment and temperature and the trends of these effects (Fig. 2) demonstrates that the phenomenon of FR-related thermal degrade is governed by kinetic/thermodynamic principles and thus is quantitative. However, these results do not conclusively reject or support the assumption of first-order kinetic theory originally postulated for phosphate-based FR systems (Pasek and McIntyre 1990, Winandy et al. 1991) and other FR systems (Woo 1981). Development of an alternative nonlinear kinetics-based modeling approach will be discussed in a later report.

Based on the results of the study reported here and previous results (Woo 1981, LeVan et al. 1990, Pasek and McIntyre 1990, Winandy et al. 1991), it is probable that mixtures of these FR chemicals would have intermediary effects. For example, if MAP and BBA were mixed, BBA would reduce the acidity of the mixture and mediate the dissociation of the MAP. This inhibition in the formation of more acid functional units would retard strength loss. On the other hand, if MAP and PA were mixed, the effects of temperature on mechanical properties over time would be proportionately less than those for PA alone, but greater than those for MAP alone. Using the convention of superposition, intermediary effects would be based on their relative proportions in a mixture. This convention is supported by preliminary data recently obtained in a cooperative effort between the Forest Products Laboratory and the University of Minnesota to develop field-applied remedial treatments for FR-treated plywood (Winandy and Schmidt 1995).

## Chemical Effects

The results of high-pressure liquid chromatography (HPLC) analysis for chemical composition of FR-treated wood are given in Table 5. Our initial observation was the slight difference between the magnitude of the reported values and that of the values reported by LeVan et al. (1990). Our HPLC technique, as reported by Pettersen and Schwandt (1991), has evolved over the last few years. Specifically, the analytical chemists and the internal laboratory standards have changed. Thus, the reported differences in chemical composition between the two reports probably reflects an interlaboratory comparison. However, relative comparisons of changes in composition at any single temperature are accurate, and general comparisons between temperature exposures are possible when comparing trends.

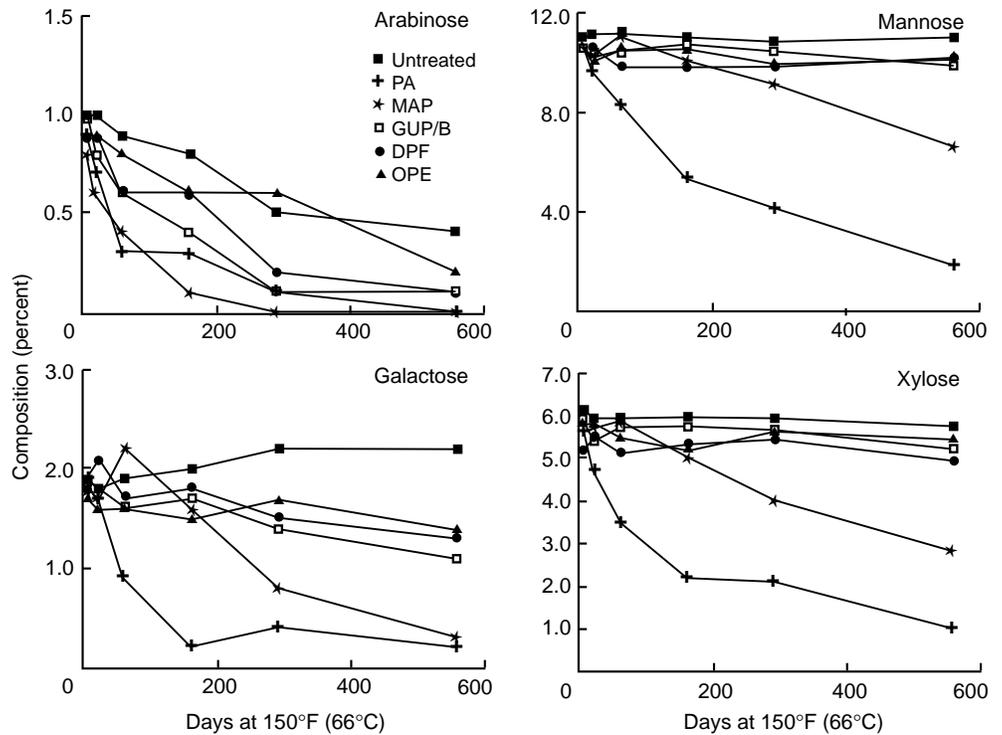
In general, hemicellulose content was significantly reduced depending on the type of FR chemical, the temperature, and the specific hemicellulose residue examined (Table 5). Overall, the individual sugars found in the hemicellulose, such as arabinose, galactose, xylose, mannose, and some glucose, were degraded whereas cellulose (i.e., the majority of the glucose reported) was largely unaffected. Klason lignin and acid-soluble lignin often increased. We suspect that the fraction collected and identified as acid-soluble lignin included both actual lignin components and carbohydrate degradation products.

The magnitude of the reduction in hemicellulose components was a function of the FR treatment and the cumulative exposure (Fig. 3). Individually, arabinose content was noticeably affected by each FR treatment on extended exposure to elevated temperature. Galactose was affected to a lesser degree than arabinose and then only by PA and MAP, whereas xylose and mannose were even less affected and again only by PA and MAP. The trends in decreasing hemicellulose residues for both untreated and FR-treated wood (Fig. 3) were directly related to the decreasing trends in MOR (Fig. 1) and WML (Table 4). These trends confirm that a systematic loss of individual hemicelluloses is highly correlated with, and may qualitatively explain, decreased strength properties, especially the increased brittleness of thermally degraded wood. It may be that interpolymeric load-sharing is reduced between hemicellulose chains as side-chain constituents (i.e., arabinose and galactose) of the hemicelluloses are degraded, and thereafter as main-chain hemicellulose constituents (i.e., xylose and mannose) are degraded. On further degradation, load sharing is systematically reduced between hemicellulose and ligneous and/or cellulosic polymers.

**Table 5—Effect of elevated temperature and duration on chemical content<sup>a</sup>**

Chemical	Exposure (days)	Klason lignin	Acid-soluble lignin	Glucose	Xylose	Galactose	Arabinose	Mannose
UNT	7	28.60	0.80	42.9	6.1	1.9	1.0	10.8
	21	28.50	0.90	42.7	5.9	1.8	1.0	11.1
	60	28.60	0.90	42.8	5.9	1.9	0.9	11.1
	160	28.20	0.90	43.1	5.9	2.0	0.8	11.0
	290	29.30	0.90	43.4	5.9	2.2	0.5	10.8
	560	29.40	1.00	42.9	5.7	2.2	0.4	11.0
PA	7	26.23	1.18	41.8	5.6	1.8	0.9	10.9
	21	27.19	1.22	40.2	4.7	1.7	0.7	9.6
	60	29.34	1.47	41.2	3.5	0.9	0.3	8.4
	160	32.96	1.94	40.5	2.2	0.2	0.3	5.3
	290	36.63	1.96	36.6	2.1	0.4	0.1	4.1
	560	44.41	2.28	32.2	1.0	0.2	0.0	1.8
MAP	7	26.59	0.99	40.8	5.6	1.8	0.8	10.6
	21	26.52	0.91	40.5	5.7	1.7	0.6	10.2
	60	27.64	1.02	42.1	5.8	2.2	0.4	11.0
	160	27.76	1.36	41.2	5.0	1.6	0.1	10.0
	290	29.33	1.45	40.6	4.0	0.8	0.0	9.1
	560	33.55	1.92	43.0	2.8	0.3	0.0	6.6
BBA	7	27.38	0.99	42.2	6.1	1.9	1.0	11.2
	21	27.49	0.96	41.8	6.4	2.0	1.0	11.1
	60	28.17	1.03	42.0	6.2	1.8	1.0	10.7
	160	28.86	1.02	43.5	6.0	2.0	0.8	11.2
	290	28.62	1.12	44.0	6.0	1.7	0.7	11.1
	560	29.32	1.16	44.1	6.3	1.9	0.8	10.9
GUP/B	7	26.90	3.11	40.5	5.9	1.7	1.0	10.6
	21	28.12	2.67	40.3	5.4	1.8	0.8	10.3
	60	28.22	2.45	40.8	5.7	1.6	0.6	10.4
	160	29.14	2.35	41.8	5.7	1.7	0.4	10.7
	290	28.91	2.25	41.7	5.6	1.4	0.1	10.4
	560	30.27	1.92	42.8	5.2	1.1	0.1	9.9
DPF	7	27.30	3.80	38.2	5.2	1.9	0.9	10.2
	21	27.80	3.10	39.7	5.5	2.1	0.9	10.6
	60	26.70	3.60	37.7	5.1	1.7	0.6	9.8
	160	27.90	2.90	38.2	5.3	1.8	0.6	9.8
	290	27.90	2.80	39.1	5.4	1.5	0.2	9.8
	560	29.20	2.50	40.1	4.9	1.3	0.1	10.1
OPE	7	26.70	0.90	40.1	5.8	1.7	0.9	10.7
	21	26.60	0.80	38.5	5.8	1.6	0.9	10.1
	60	26.40	1.00	38.5	5.5	1.6	0.8	10.5
	160	26.20	1.20	39.2	5.2	1.5	0.6	10.5
	290	27.10	1.10	39.9	5.6	1.7	0.6	9.9
	560	28.30	1.10	41.4	5.4	1.4	0.2	10.1

<sup>a</sup>All tests were conducted at 150°F (66°C). Values are percentages of total content.



**Figure 3—Effect of various durations of exposure at 150°F (66°C) on chemical composition for untreated and fire-retardant-treated wood.**

Finally, note that the rate of this loss in arabinose, galactose, xylose, and mannose is systematic in that it is dependent upon both exposure temperature and cumulative duration at that exposure temperature (Fig. 4), as is strength loss (Figs. 1 and 2). Specifically, it appears that thermal degrade of carbohydrates in untreated wood is related to thermal degrade of PA, MAP, and GUP/B by the inverse of the dissociation potential ( $K_d$ ) for each evaluated FR (Table 2, Fig. 4). We believe that this relationship is potentially quantitative because of the consistency between strength loss and changes in chemical composition. This wood strength–chemistry relationship will be explored in a future report.

## Conclusions

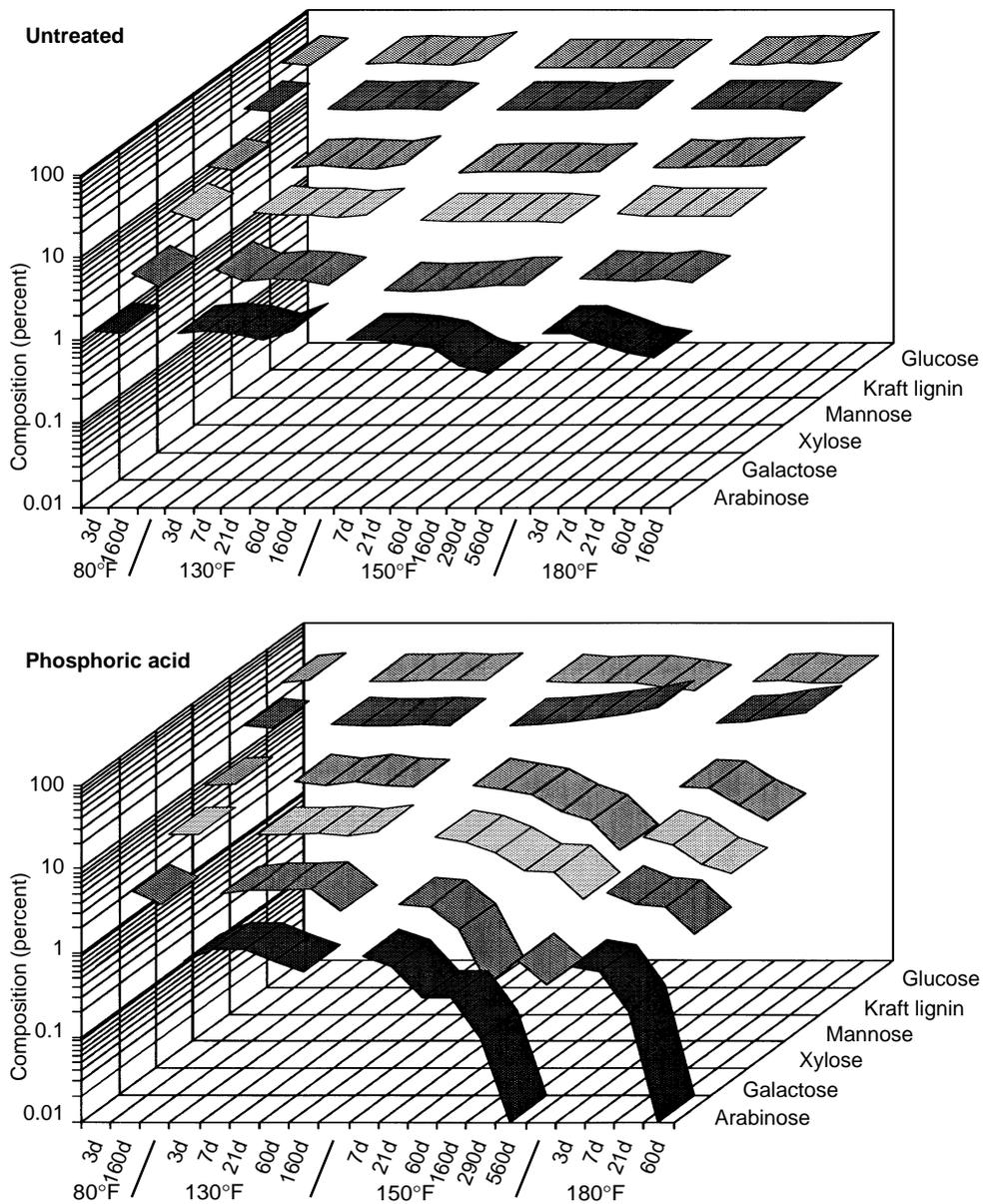
The results presented in this report for fire-retardant- (FR-) treated wood exposed at 150°F (66°C) are consistent with previous results of matched material exposed at 130°F (54°C) and 180°F (82°C). Together, the combined data clearly show that the phenomenon of FR-related thermal degrade is systematic and potentially quantitative. The results also support the hypothesis that the lower the pH of the FR-treated wood and/or the dissociation energy of the FR treatment in the wood, the higher the rate of strength loss over time.

An evaluation of changes in the chemical composition of wood clearly indicated that hemicellulose is the key component of thermal-related strength loss. Although this finding does not minimize the critical importance of cellulose and lignin in the overall initial strength of wood products, these results do show that when wood is viewed as a collection of organic components, the degradation of hemicellulose almost exclusively accounts for the first 10- to 25-percent loss in initial strength. The relationship between changes in chemical composition, especially loss in hemicellulose composition, and strength appears quantitative.

The data from this study as well as data from the study by LeVan et al. (1990) have been used to develop a nonlinear kinetics-based model to predict strength loss from FR-related thermal degrade. That report is in progress. Further plans call for us to validate that model by evaluating 3- and 5-year exposures.

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**Figure 4—Cumulative change in chemical composition after various durations of exposure at 80°F (27°C), 130°F (54°C), 150°F (66°C), and 180°F (82°C).**

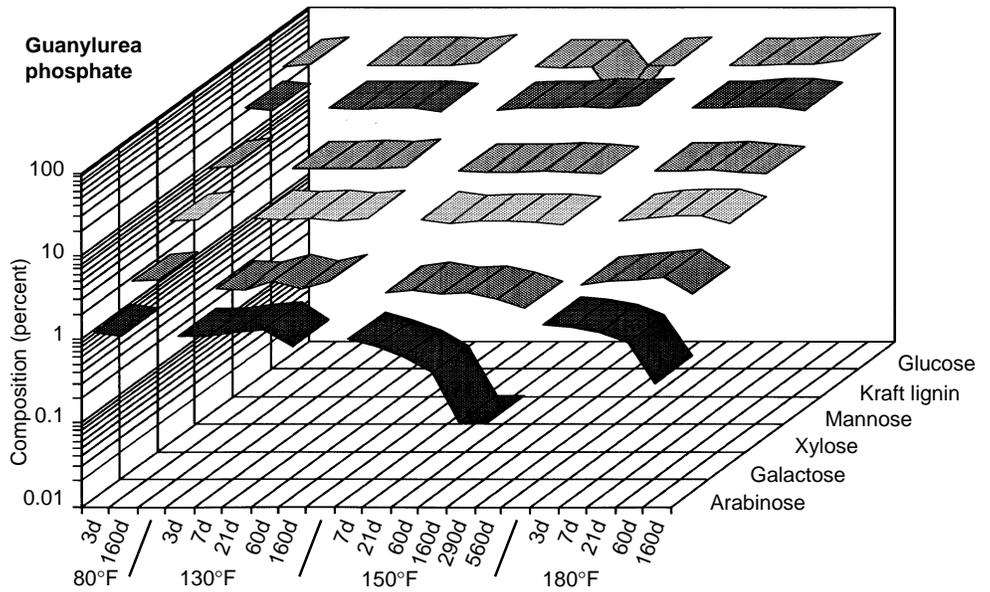
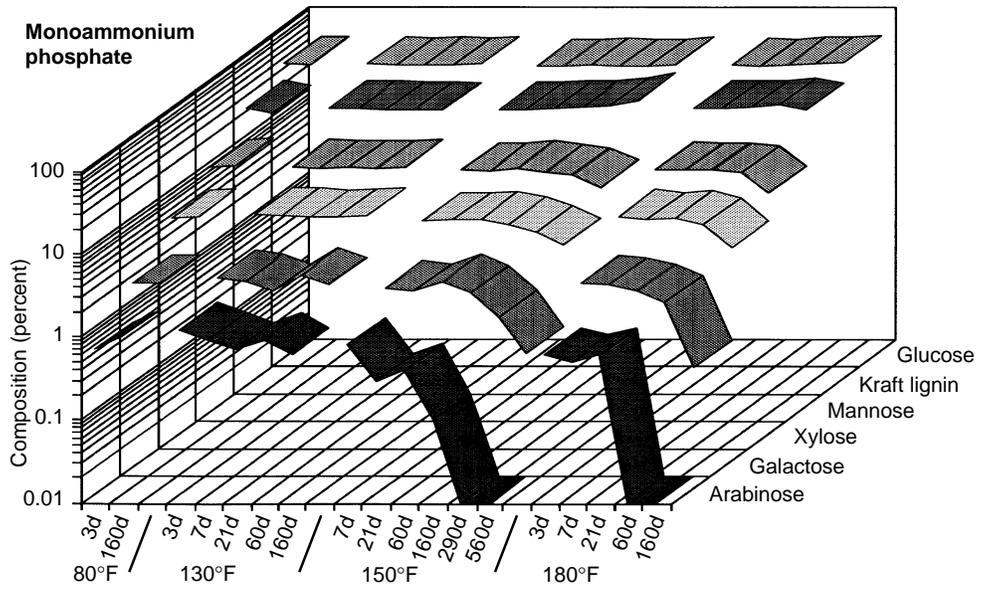


Figure 4—Continued.