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Redrying Fire - Retardant - Treated Structural Plywood *1

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— 構造用 耐火處理 合板의 再乾燥에 關한 研究 — *1

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ABSTRACT

Exterior grades of Douglas-fir and aspen plywood were impregnated with interior fire-retardant chemicals and redried under low-, intermediate-, and high-temperature drying conditions. Fire-retardant treatments included borax-boric acid, chromated zinc chloride, minalith, pyresote, and a commercial formulation. Drying processes included kiln and press-drying. Evaluated were drying rates and defects generated. The borax-boric acid and the commercial treatments redried at rates similar to water-treated controls. Other salt treatments were significantly slower drying and more defect prone. Chromated zinc chloride treatment was consistently the slowest drying and most defect prone. Press drying was three times faster at an equivalent temperature level. However, thickness shrinkage doubled because of 50 1b/in.^{2} platen pressure.

摘 要

美松 및 포푸라 耐水合板을 內裝用耐火劑로 加压處理한 다음 低溫, 中溫 및 高溫乾燥狀態에서 再乾燥를 實施하였다, 硼砂-硼酸, 크롬化 塩化亞鉛, 미나리스, 파이레소오트 및 一種의 商業用 耐火劑로 耐火處理를 實施하였다。 乾燥方法은 키른乾燥와 熱板乾燥를 適用하였으며 乾燥速度와 乾燥缺陷에 關하여 檢討하였다.

硼砂-硼酸은 水分處理合板과 類似한 乾燥速度를 나타내었으나 其他의 耐火劑는 一層 늦은 乾燥速度를 나타내었고 더 많은 乾燥缺陷을 일으키는 傾向이 있었다。 特히 크롬化 塩化亞鉛은 가장 乾燥速度가 느렸으며 가장 많은 乾燥缺陷을 일으키는 傾向이 있었다.

熱板乾燥는 키른 乾燥와 比較하여 같은 溫度水準에서 三倍나 더 빨리 乾燥하였으나 熱板压力을 50 1b/in^2 (3.52 kg/cm^2)를 適用하였기 때문에 두께 收縮率은 二倍를 나타내었다.

Kewwords: Fire retardants, structural plywood, Douglas-fir, aspen, thickness shrinkage, kiln drying, press drying, borax-boric acid, chromated zinc chloride, minalith, pyresote.

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INTRODUCTION

Among the means to reduce fire hazard in buildings employing wood are fire-retardant treatments. Most past studies of the fire-retardant treatment of wood have focused either on the fire retardant's effect on achieved fire retardancy or on the resultant mechanical properties. One of the steps considered important to successful treating is redrying after fire-retardant treatment. Many problems affecting the plywood quality and cost can occur during the redrying of fire-retardant-treated (FRT) plywood. Among these are a decrease of fire-retardant effectiveness due to the leaching and evaporation of impregnated chemicals, drying rate (which greatly affects the time to completion, and the cost, of fire-retardant treatment), and various types of degrade appearing during redrying process.

To produce commercially acceptable treated wood at low cost requires treating and redrying as rapidly as possible. An effective fire-retardant treating process must be compatible with redrying.

Current specifications (AWPA, 1974) for the redrying of FRT plywood require that:

1. After treatment, material shall be air-dried or kiln-dried to an average moisture content of 15% or less.
2. During kiln-drying, the dry-bulb temperature of the kiln shall not exceed 160°F until the average moisture content of the wood has dropped to 25% or less.

This study examines the effects on the plywood quality following redrying after fire-retardant treatment using increasingly higher-temperature drying regimes. The results of different redrying processes for several fire-retardant-treatment chemicals are compared.

CRITICAL LITERATURE REVIEW

Only Mackay (1978) has reported research that deals wholly with the redrying of FRT plywood, though other important related studies on FRT wood have been done by King and Matteson (1961), Jessome (1962), Johnson (1967, 1979), and Gerhards (1970).

King an Matteson (1961) studied the effect of fire-retardant treatments on the mechanical properties of 1/4-inch-thick A-C exterior Douglas-fir plywood and evaluated mechanical strength (such as static bending, shear-through-the-thickness, and Izod-impact) to compare treated and untreated plywood after conditioning at 50% RH and 75° F for several weeks.

In that research the material was commercially treated and redried, hence no information is available on the redrying conditions.

Jessome (1962) studied the strength properties of small, clear specimens of Douglas-fir, red pine, and 3/8-inch-thick Douglas-fir plywood, and compared treated and untreated samples in static bending and toughness. Plywood treated with ZAB (zinc-chloride-ammonium sulfate-boric acid type), APS I (ammonium phosphate-ammonium sulfate type) and APS II (ammonium phosphate-ammonium sulfate type consisting of ingredients with different properties than APS I) were kiln dried by schedules of maximum dry-bulb temperature of 150°F and wet bulb of 130°F to attain approximately 12% MC.

Like King and Matteson (1961), Jessome (1962) provided little insight into the redrying conditions and results. He simply stated that drying continued until the materials reached equlibrium (12%) and that drying times "ranged up to 2-1/2 weeks" for 2- x 2- x 30-inch specimens.

Mackay (1978) studied the kiln drying of 1/2- and 3/4-inch-thick Douglas-fir sheathing plywood treated with CCA (chromated copper arsenate), and 1/4-inch-thick plywood treated with a 5% fire-retardant formulation consisting of an aqueous solution of ammonium sulfate and borax.

CCA-treated plywood panels were dried at 145/

140, 165/160, 185/180, and 205/200°F dry-/wet-bulb initial temperature. A constant dry bulb was maintained and the wet bulb decreased 1°F per hour in each run.

The 1/4-inch-thick FRT plywood was redried using an intial 160°F dry bulb and 10°F wet-bulb depression and then maintaining constant conditions or raising dry-bulb temperatures from 3 to 5°F per hour and decreasing wet bulb 3 to 5°F per hour. He concluded that the redrying of 1/4-inch plywood at maximum drying rate with minimum surface checking could be best achieved with a 3°F increase in dry bulb and 3°F decrease in wet bulb per h. In that case the drying rate was 2.65%per h from an initial level of 78.6% moisture content.

Johnson (1967) employed two unidentified commercial treatments in Douglas-fir. Half of the 2 x 6 material was redried by air drying and the other half by kiln drying. One treatment was kiln dried in 72 h with dry bulb ranging from 148 to 158°F and wet bulb from 110 to 95°F. The second treatment was kiln dried in 216 h with 140°F dry bulb and a wet bulb from 129 to 116°F. The thicknesses of the lumber after redrying were 96 and 97% of unseasoned thickness.

King and Matteson (1961) and Jossome (1962) limited their work to evaluation of the mechanical properties of plywood samples under one fixed drying condition after treatment with some fire-retardant chemicals. Only Johnson (1967) and Mackay (1978) considered surface defects and drying rates for various conventional kiln schedules for redrying.

Koch (1964), Lutz (1974), Lutz et al. (1974), and Chen (1978) reported the use of comparatively low platen temperature (around 350°F) in press drying of untreated thin veneer or lumber not less than 1/2-inch thick. The average pressure was 50 lb/in², but ranged to 100 lb/in². Heebink and Compton (1966), Hittmeier et al. (1968), Haygreen and Turkia (1968), Turkia and Haygreen (1968), and Chen and Biltonen (1979) studied press drying at conditions of 300 to 350°F plate temperature and 25 to 150 lb/in.² in press pressure for half-inch or thicker wood products. From their results, it can be concluded that the ideal platen temperature and pressure in press drying of 1/2-inch or thicker wood is 350°F and 50 lb/in² pressure.

Hittmeier et al. (1968) dried 1/2-inch-thick material to 4 to 6% MC in 25 to 75 min, depending on the species and initial moisture content, and 1-inch-thick material to the same MC in 100 to 200 min, all at 345°F and 50 lb/in².

MATERIALS AND METHODS

Specimens and treatments

Test panels of 5-ply, A-C exterior-grade Douglas-fir plywood and aspen plywood were obtained directly from manufacturers. The 4- x 8-foot x 5/8-inch Douglas-fir and 4- x 4-foot x 5/8-inch aspen panels were cut into 1- x 2-foot sections for the fire-retardant treatment. The samples were sequentially marked and stacked for conditioning in a controlled humidity room at 65% RH and 75°F for several weeks.

When panel weights equalized, all dimensions and weights were recorded and moisture content and specific gravity calculated for each before treatment. The samples were randomly classified into treating groups. Excluded were samples with visible defects and inadequate sections. Each group consisted of 40 samples each of Douglas-fir and aspen species, with the exception of the untreated group of 20 samples each of Douglas-fir and aspen.

The panels were treated with six preparations--A, borax-boric acid; B, chromated zinc chloride; C, minalith; D, pyresote; E, a commercial preparation[3/]; and W, a water treatment--the chemical compositions of which are given in Table 1. The seventh group was the untreated control.

The target chemical retention selected for this study was 5 lb per cubic foot (lb/ft³) on dry salt

[3/] A preparation of undisclosed chemical composition from Koppers Company, Inc., Pittsburgh, Pa.

Table 1. **Fire-retardant chemicals types, composition, and grouped sample numbers**

Treatment designation	Chemical types	Composition	Ratio
			%
A	Borax-Boric Acid		
		Borax	60
		Boric acid	40
B	Chromated Zinc Chloride		
		Chromate zinc chloride	80
		Ammonium sulfate	10
		Boric acid	10
C	Minalith		
		Diammonium phosphate	10
		Ammonium sulfate	60
		Anhydrous sodium tetraborate	10
		Boric acid	20
D	Pyresote		
		Zinc chloride	35
		Ammonium sulfate	35
		Boric acid	25
		Sodium dichromate	5
E	Non-COM F		
		Proprietary formulation of Koppers Company, Inc.	--
W	Water Treatment (Control Group)	Water	100

basis. To obtain this retention for Douglas-fir and aspen, slightly different full-cell-process treating procedures were applied. Specimens were treated in a small cylinder in an experimental treating plant. Each group of Douglas-fir plywood was treated on a schedule of: 22-inch initial vacuum for 45 min., injection of solution at 150° F, 150 lb/in.^{2} final pressure, and a 3-h holding period after reaching final pressure. Each group of aspen plywood was treated employing: 22-inch initial vacuum for 30 min., injection of a solution at 150°F, 150 lb/in.^{2} final pressure, and a 2-h holding period after attaining final pressure.

Mean salt retention and ranges for each chemical (Table 2) are only slightly greater than the originally proposed 5 lb/ft^3. The average treated retentions in this study were 5.36 lb/ft^3 in Douglas-fir and 5.36 lb/ft^3 in aspen plywood. The treating salt solution contained 15% salt by weight.

After treatment, all treated samples were put

Table 2. Range (and mean)[a/] of chemical retentions of treated Douglas-fir and aspen plywood

Treatment designation	Douglas-fir plywood			Aspen plywood		
	Specimen specific gravity[b/]	Impregnated solution	Chemical retention	Specimen specific gravity	Impregnated solution	Chemical retention
		Lb/ft³	Lb/ft³		Lb/ft³	Lb/ft³
A	0.470-0.573 (0.513)	32.9-40.7 (36.1)	4.9-6.1 (5.4)	0.455-0.515 (0.478)	32.7-39.7 (36.6)	4.9-6.0 (5.5)
B	0.478-0.562 (0.511)	31.1-41.8 (35.2)	4.7-6.3 (5.3)	0.451-0.509 (0.476)	30.7-40.9 (37.0)	4.6-6.1 (5.5)
C	0.477-0.567 (0.516)	32.4-40.3 (35.6)	4.9-6.0 (5.3)	0.451-0.518 (0.483)	30.8-38.4 (34.6)	4.6-5.8 (5.2)
D	0.477-0.563 (0.514)	30.5-41.1 (35.9)	4.6-6.2 (5.4)	0.425-0.515 (0.480)	31.6-37.1 (34.9)	4.7-5.6 (5.2)
E	0.471-0.552 (0.511)	13.7-23.3 (20.0)		0.455-0.514 (0.483)	18.3-27.2 (22.7)	
W	0.472-0.566 (0.516)	30.3-36.8 (32.9)		0.455-0.515 (0.478)	32.7-39.7 (36.6)	

a/ Mean values of tested specimens are in parentheses.
b/ Based on volume at test and weight when equalized at 65% RH and 95°F.

into polyethylene bags according to chemical type and stored in a cold room (40°F) until required for the redrying tests.

Drying procedures

For drying treated specimens, four conventional and three high-temperature kiln drying runs and three press drying schedules were used.

In conventional and high-temperature drying, stacks of 48 specimens composed of 24 Douglas-fir and 24 aspen samples were used in each run. The stacks were generated by the random selection of four specimens from each of five (A, B, C, D, E) fire-retardant-treated sample groups and the water-treated control group (W). A specially designed rack separated the stacks of panels by a 7/8-inch space. Before drying, the weight and thickness of treated specimens were measured to obtain the initial moisture content and thickness.

Conventional drying runs were discontinued briefly every 12 h to measure weight losses of water-treated control samples. Initial dry-bulb/wet-bulb temperatures of four runs in conventional kiln drying were 120/115, 140/135, 160/155, and 180/175°F. As drying progressed, the dry-bulb temperature was raised 5°F for all but the 180/175°F schedule to a maximum of 180°F, and wet-bulb temperatures were dropped 5°F every 12 h until the scheduled target weight for the water-treated specimens was attained. In the 180/175°F schedule, the dry-bulb temperature was held constant and the wet-bulb decreased. The air velocity through the racked specimens in the four runs was maintained at 450 feet per minute (ft/min). Only the specimens of water-treated groups were used as sample boards to obtain weight loss values every 12 h until the target weight was attained. The target moisture content for these sample boards was 8 to 10%.

Only the schedule with an initial dry-bulb temperature of 120°F did not subject the treated panels to dry-bulb temperatures of 160°F before reaching specimen moisture content of 25% or less (per AWPA 1974 recommendations).

For the three runs of high-temperature drying, the initial dry-bulb/wet-bulb temperatures were 200/190, 230/190, and 260/190°F. As the drying progressed, the dry- and wet-bulb temperatures were kept constant until target weights for the water-treated specimens were reached. Air velocity through the racked specimens in the three runs of high-temperature drying was 650 ft/min.. Because of rapid drying, 12 h was adequate time to attain the target weight of the water-treated specimens. At that time, the charge was removed.

In press drying, platen temperatures were 250, 300, and 350°F and platen pressure was 50 lb/in.^{2}. Perforated aluminum cauls above and below samples were used between hot plates. Plates were perforated with 1/8-inch holes every inch. Grooves vented the holes to the plate edges. Four treated samples were dried at a time. The press was opened every 30 min. to measure weight loss of all of the specimens as a group. Drying was stopped if the batch was near average target weight of specimens. The final drying target was a 10 to 12% MC. Thickness before and after drying were measured to calculate thickness shrinkage.

RESULTS AND DISCUSSION

Drying rates can often be effectively calculated and compared by assuming the rate of drying is proportional to the moisture content, u, at any drying time, t (e.g., Tschernitz and Simpson, 1979).

The drying rates were obtained in two ways:

1. By calculating the mean rate of drying by dividing the difference between initial moisture content, u_0, and final moisture content, u_f, by the total drying period, t'.
2. By calculating a drying rate constant, K,

that is proportional to the moisture content, u, at any drying time, t.

The first method is of practical interest, but the second often linearizes drying rate behavior and can include dependency on drying temperature, t, in a rational manner. Using the second method,

$$\frac{d(u)}{dt} = -K(u)$$

$$\int_{u_o}^{u} \frac{du'}{u'} = -\int_{0}^{t'} K\,dt$$

$$\ell n(u/u\ ) = -Kt'$$

The factor, K, is a function of environment vapor pressure, p, and material thickness, ℓ (Simpson and Tschernitz, 1980):

$$K = (c_0 + c_1\,p) / \ell^n$$

The vapor pressure of pure water, p (mmHg), can be related to temperature, T (°K), within the range of 110 to 180°F by the expression:

$$p = \exp(20.41 - 5132/T)$$

K is a direct function of environment temperature, T. If this is the actual case, plotting the logarithm of moisture content with time should yield straight lines of negative slope, K, when drying is conducted in a constant temperature environment having a sufficiently low partial vapor pressure of water to have drying of the wet material occur. The factor, K, can be interpreted as an alternate form of the drying rate. The constants, C_0 and C_1, will vary with species or product, and treatment. In particular, fire-retardant treatments that have saturated solution vapor pressures, p_0, lower than that of water will decrease the drying rate compared to water-treated specimens when within equivalent environmental partial vapor pressures, p. The saturated solution vapor pressures can be obtained by dew point measurements at room temperature (and converted to relative humidities) for all the fire-retardant solutions except Type E (Table 3).

Drying curves for all redrying processes are plotted (Figs. 1-10) using this approach.

Table 3. Saturated vapor pressures and relative humidities of atmospheres over saturated treatment solutions at room temperature

Treatment type	Saturated vapor pressure	Relative humidity
	mm Hg	%
A	16.85	76.9
B	13.60	62.8
C	14.73	70.3
D	17.27	83.2
E	--	--
Water	22.40	100.0

Conventional kiln drying

The drying times, mean drying rates, final dry-bulb temperature, and initial and final moisture content were determined for 5/8-inch-thick Douglas-fir plywood and aspen plywood treated by five fire-retardant chemicals and one water-treated control group in conventional kiln-drying runs (Tables 4 and 5).

Figures 1 and 2 are the resulting drying curves for conventional drying runs of water-treated Douglas-fir and aspen plywood. Non-linearity in these conventional kiln-drying derived results is attributable to nonconstant dry- and wet-bulb kiln temperatures. As expected, the drying times decreased with increased drying temperature, and drying curves of lower temperatures are similar in shape to the curves at higher temperatures.

As previously stated, drying data other than initial and final moisture content for the chemically

Table 4. **Drying times, drying rates and shrinkage values of 5/8-inch-thick *treated Douglas-fir plywood dried with conventional kiln schedules***

Initial temperature schedule, Dry bulb/wet bulb	Drying time	Final dry-bulb temperature	Treatment designation	Initial MC	Final MC	Drying rate [a]	Thickness shrinkage
°F	h	°F		%	%	% MC/h	%
120/115	96	155	A	105.0	7.8	1.01	6.3
			B	106.3	29.4	.80	6.3
			C	109.2	13.3	1.00	3.5
			D	111.8	15.8	1.00	5.1
			E	59.0	1.0	.60	4.5
			W	133.9	6.4	1.33	5.8
140/135	84	170	A	116.9	9.0	1.28	2.7
			B	109.9	30.8	.94	1.3
			C	106.6	10.7	1.14	2.1
			D	107.8	14.7	1.11	3.3
			E	57.9	2.0	.67	2.4
			W	128.0	6.9	1.44	6.3
160/150	60	180	A	113.8	11.9	1.70	2.6
			B	108.7	34.2	1.24	2.2
			C	103.8	17.0	1.45	1.5
			D	113.7	18.1	1.59	2.8
			E	59.6	4.3	.92	.5
			W	128.1	8.3	2.00	3.8
180/175	54	180	A	105.7	8.3	1.80	3.1
			B	117.6	35.3	1.52	1.8
			C	107.3	14.0	1.73	1.6
			D	106.2	14.7	1.69	1.9
			E	60.0	3.5	1.04	1.5
			W	131.9	8.6	2.28	4.2

a/ Calculated as $\frac{\text{Initial MC} - \text{Final MC}}{\text{Drying time}}$

Table 5. Drying times, drying rates and shrinkage values of 5/8-inch-thick *treated aspen plywood dried with conventional kiln schedules*

Initial temperature schedule, Dry bulb/wet bulb	Drying time	Final dry-bulb temperature	Treatment designation	Initial MC	Final MC	Drying rate[a]	Thickness shrinkage
°F	h	°F		---- %	---	% MC/h	%
120/115	96	155	A	119.0	9.6	1.14	6.5
			B	131.1	31.1	1.04	8.7
			C	126.3	14.9	1.16	5.4
			D	119.0	11.7	1.12	6.9
			E	74.4	5.4	.72	3.5
			W	154.8	7.4	1.54	5.6
140/135	84	180	A	124.4	11.1	1.35	6.1
			B	128.8	29.6	1.18	10.3
			C	118.6	13.1	1.26	5.5
			D	119.1	13.7	1.25	4.8
			E	79.9	5.1	.89	3.0
			W	148.2	8.4	1.66	6.3
160/155	60	180	A	121.2	12.2	1.81	3.9
			B	127.2	31.8	1.59	8.5
			C	114.3	16.7	1.63	1.5
			D	124.5	17.6	1.78	3.9
			E	71.9	7.2	1.08	2.3
			W	148.8	9.8	2.32	5.9
180/175	54	180	A	129.6	12.5	2.17	5.7
			B	126.6	31.2	1.77	12.2
			C	121.3	18.0	1.91	1.4
			D	118.7	15.0	1.92	4.5
			E	85.7	7.0	1.46	2.1
			W	156.0	9.1	2.72	5.4

a/ $\frac{\text{Initial MC} - \text{Final MC}}{\text{Drying time}}$

...d specimens was not obtainable for the kiln-drying conditions. One can, however, expect that similar drying curves would be obtained.

The final moisture content levels for water-treated sample boards in the four conventional drying runs were intended to be 8 to 10%. However, the attained levels were 6.4 to 8.6% in Douglas-fir and 7.4 to ?.8% in aspen-treated plywood. Final moisture contents for the FRT specimens in the same drying run were higher except for the E-type treatment. One cannot compare this treatment directly with other chemical types because it evidently differed in initial impregnated weight. With the exception of water control and E-type-treated plywood, A-Type-treated specimens attained target moisture contents in the shortest drying time in both Douglas-fir and aspen plywoods for all four conventional drying runs. The specimens of B-treated type were always the slowest in drying and had the highest final moisture content. The average final moisture contents of treated specimens, including water-treated control and E-treated type, after the four conventional kiln drying runs ranged from 12.3 to 15.6% in Douglas-fir and 13.3 to 15.9% in aspen. Because of the wide difference in drying rates for the mixed treated panels, it was impractical to bring them all to the same equivalent final moisture content. Drying rates increased with temperature for all five chemical-treated types. Aspen-treated plywood dried more rapidly than Douglas-fir in each of four runs. The drying rates in Tables 4 and 5 characterize the drying differences for the various kiln temperatures and chemical treatment types.

Mackay's (1978) results for CCA-treated FRT plywood showed mean drying rates generally less than, but similar to, those observed in this study.

High-temperature kiln drying

The high-temperature kiln drying decreased drying times (Table 6 and 7) more than did conventional kiln drying. As in conventional drying, decreases were proportional to increases in drying temperature. Some treated types were over-dried in the 260/190°F run. As in conventional kiln drying, in the lowest temperature run of 200/190°F, B-, C-, and D-type-treated plywoods were not easily dried, whereas

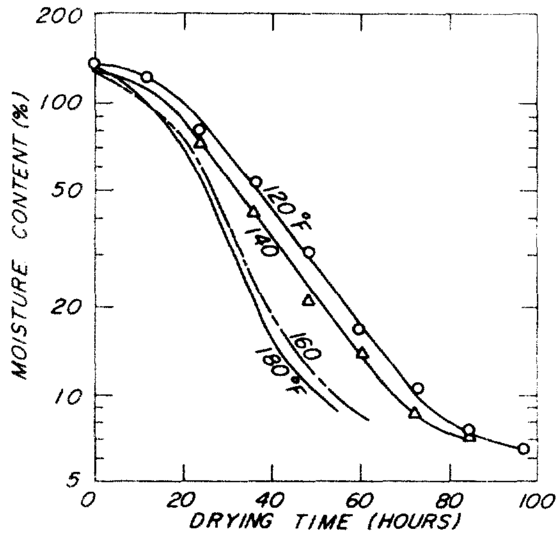

Fig. 1. Conventional drying curves of water-treated Douglas-fir plywood.

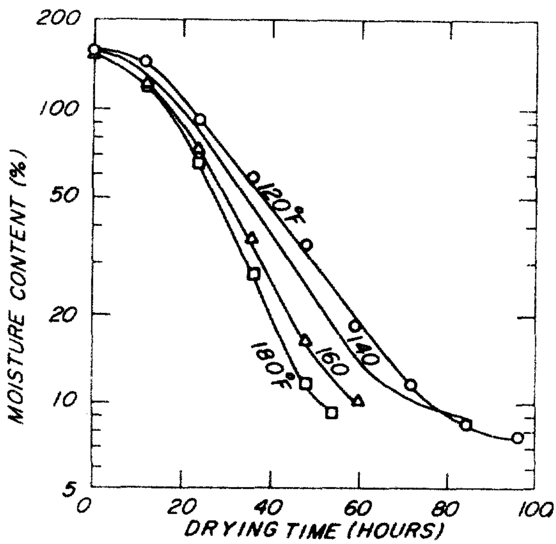

Fig. 2. Conventional drying curves of water-treated aspen plywood.

Table 6. Drying times, drying rates and shrinkage values of 5/8-inch-thick treated Douglas-fir plywood dried with high-temperature kiln schedules

Initial tempera-ture scheduled, Dry bulb/wet bulb	Drying time	Treatment designation	Initial MC	Final MC	Drying rate [a]	Thickness shrinkage
°F	h		——— %	———	% MC/h	%
200/190	46	A	106.6	11.0	2.08	4.4
		B	114.3	43.5	1.54	1.9
		C	106.6	20.6	1.87	3.7
		D	109.5	21.0	1.92	1.4
		E	59.2	7.2	1.13	2.1
		W	131.9	11.7	2.61	3.3
230/190	15	A	111.5	8.2	6.89	2.3
		B	108.9	32.6	5.09	2.5
		C	107.7	14.5	6.21	2.3
		D	106.0	15.0	6.07	3.0
		E	57.0	2.4	3.64	1.8
		W	132.8	8.0	8.32	4.1
260/190	12	A	113.3	3.8	9.13	3.8
		B	106.1	20.0	7.18	3.7
		C	102.4	5.4	8.08	5.3
		D	112.0	8.7	8.61	4.4
		E	62.5	1.5 [b]	5.33	2.4
		W	125.7	4.7	10.08	7.9

a/ $\frac{\text{Initial MC} - \text{Final MC}}{\text{Drying time}}$

b/ Over dried.

Table 7. Drying times, drying rates and shrinkage values of 5/8-inch-thick treated aspen plywood dried with high-temperature kiln schedules

Initial temperature scheduled, Dry bulb/wet bulb	Drying time	Treatment designation	Initial MC	Final MC	Drying a/ rate	Thickness shrinkage
°F	h		---- %	----	% MC/h	%
200/190	46	A	124.8	14.1	2.41	4.1
		B	131.0	40.1	1.97	9.9
		C	118.0	22.8	2.07	1.4
		D	122.4	21.1	2.20	4.6
		E	75.9	10.4	1.42	3.1
		W	153.7	11.8	3.09	6.4
230/190	15	A	129.7	12.6	7.81	2.9
		B	125.6	30.6	6.33	12.9
		C	115.7	16.8	6.59	1.6
		D	114;3	15.7	6.58	5.1
		E	80.4	5.0	5.03	2.6
		W	154.6	9.4	9.68	7.3
260/190	12	A	134.6	6.1	10.71	5.5
		B	133.7	21.3	9.37	17.9
		C	117.8	8.7	9.09	6.6
		D	125.6	10.9	9.55	8.9
		E	77.6	2.3	6.27	3.9
		W	150.8	5.9	12.08	8.4

a/ $\frac{\text{Initial MC} - \text{Final MC}}{\text{Drying time}}$

A-type- and water-treated specimens were readily dried to near the target moisture content both in Douglas-fir and aspen. At 230/190 and 260/190°F, panels were dried very rapidly in comparison to the 200/190°F level. The drying rates of water-treated control were the highest. The difference in drying rates between 200/190°F and other runs was larger than that between 230/190 and 260/190°F runs, (Figs. 3 and 4). As mentioned previously, only the initial and final moisture contents for the other five FRT plywoods were available for the conventional and high-temperature kiln drying. This does not allow the plotting of drying curves. It can be expected that the drying curves for the chemically treated specimens would be similar in shape to those in Figures 3 and 4 for the water-treated materials.

Kimball and Lowery (1967) found greater variation in final moisture contents of high-temperature-dried lodgepole pine and western larch studs. However, increased variation in final moisture contents was not observed among treated chemical types subjected to either high-temperature or conventional drying. There was much variation, however, in the mean drying rates among treated types for high-temperature drying compared with conventional drying. It is thought that drying rates sharply increase with an increase of temperature in high-temperature drying and magnify the variation among treated chemical types more than in conventional runs. This was especially reflected in this study in drying times to final moisture contents in which large differences between 200/190 and 230/190 or 260/190°F were found. Very long drying times (46 h or more) were required at 200/190°F, but only 15 h at 230/190°F and 12 h or less at 260/190°F (Figs. 3 and 4).

Press drying

The drying times, initial and final moisture content, and mean drying rates for press drying are given in Tables 8 and 9. Drying curves at platen temperatures of 250, 300, and 350°F for treated Douglas-fir and aspen plywood are shown in Figures 5 through 10. Final moisture contents at each of the scheduled

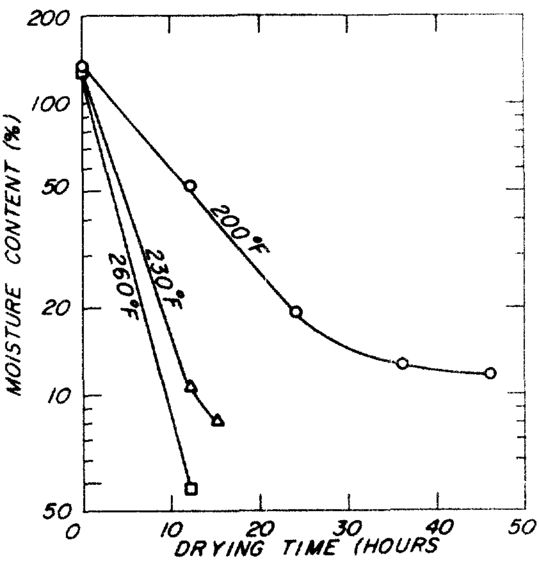

Fig. 3. **High-temperature drying curves of Douglas-fir plywood.**

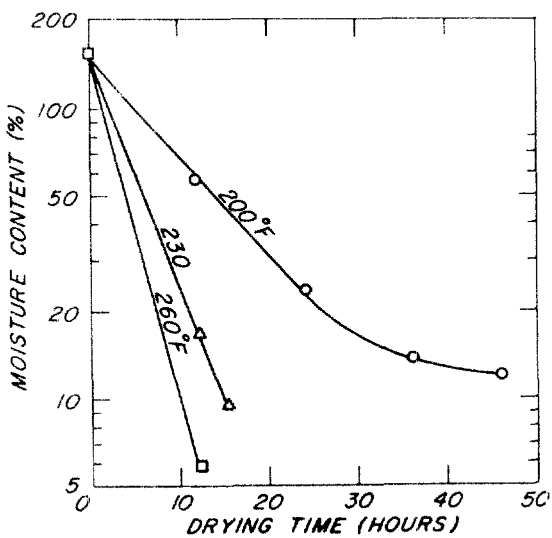

Fig. 4. **High-temperature drying curves of aspen plywood.**

drying temperatures reached the originally targeted 10 to 12% although slight variations appeared among treated types at the same drying temperature.

Differences in drying time are clearly functions of treatment or initial moisture content (Fig. 5). These differences decrease between drying curves as the drying temperature increases (Figs. 6 and 7). These tendencies are even more distinct in treated aspen plywood (Figs. 8, 9, and 10). Accordingly these phenomena imply that drying time can be decreased considerably by drying at temperatures of 300 or 350°F. These results appear independent of chemical or water treatment in that the high temperature in press drying decreases the differences in drying effect among treated types. B-type-treated plywood was generally the most difficult to dry. A-type-treated plywood dried more rapidly than water-treated plywood at 250°F. However, at 300 and 350°F, the water-treated panels were more easily dried, as would be expected. The mean drying rates exhibit great variation among treated types at each drying temperature (Tables 8 and 9).

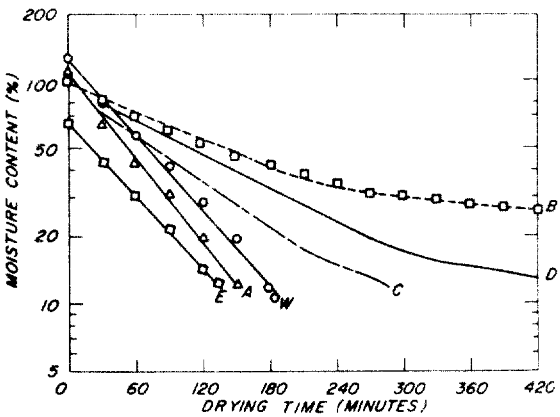

Fig. 5. Press drying curves of Douglas-fir plywood at 250°F.

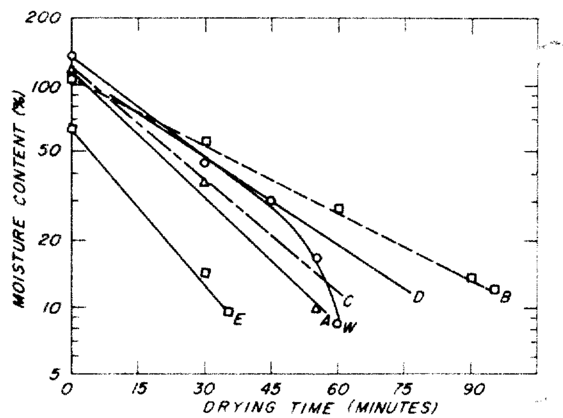

Fig. 7. Press drying curves of Douglas-fir plywood at 350°F.

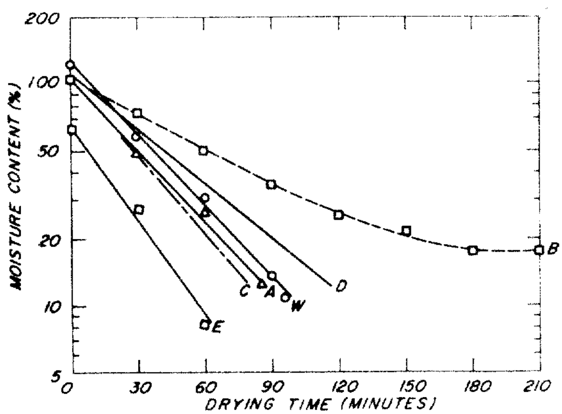

Fig. 6. Press drying curves of Douglas-fir plywood at 300°F.

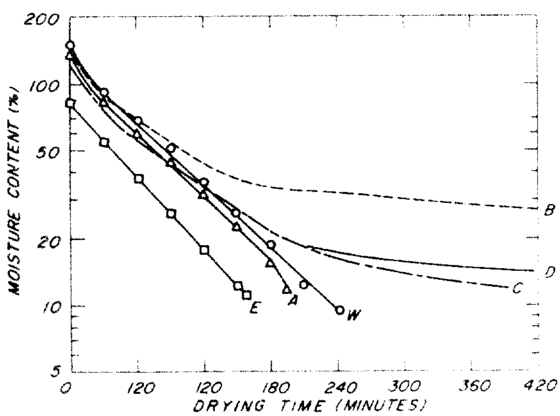

Fig. 8. Press drying curves of aspen plywood at 250°F.

Table 8. Drying times, drying rates and shrinkage values of press-dried[a/] 5/8-inch-thick treated Douglas-fir plywood

Drying run	Treatment designation	Drying time	Initial MC	Final MC	Drying[b/] rate	Thickness shrinkage
°F		h (min.)	------- % -------		% MC/h	%
250	A	2.50 (150)	109.9	12.0	38.17	8.3
	B	14.50 (870)	102.9	19.8	5.72	11.9
	C	4.83 (290)	112.9	11.8	20.92	7.6
	D	7.58 (455)	106.6	12.0	12.48	9.1
	E	2.25 (135)	64.1	11.4	23.41	6.4
	W	3.08 (185)	123.7	11.0	36.56	12.2
300	A	1.42 (85)	104.6	11.4	65.82	7.7
	B	7.50 (450)	104.1	12.0	12.27	21.9
	C	1.33 (80)	110.5	11.9	73.92	7.7
	D	1.92 (115)	108.6	12.0	50.39	7.9
	E	1.00 (60)	62.4	8.3	54.09	7.1
	W	1.58 (95)	122.1	10.9	70.18	11.1
350	A	0.92 (55)	114.0	9.8	113.75	9.1
	B	1.58 (95)	107.5	12.0	60.36	21.3
	C	1.00 (60)	119.0	10.8	108.25	9.3
	D	1.16 (70)	112.3	12.2	85.73	8.6
	E	0.58 (35)	62.6	9.3	91.22	6.7
	W	1.00 (60)	132.2	8.5	123.72	12.7

a/ 50 $lb/in.^2$

b/ $\frac{\text{Initial MC} - \text{Final MC}}{\text{Drying time}}$

Table 9. Drying times, drying rates and shrinkage values of press-dried[a/] 5/8-inch-thick treated aspen plywood

Drying run	Treatment designation	Drying time	Initial MC	Final MC	Drying[b/] rate	Thickness shrinkage
°F		h (min.)	------- %	-------	% MC/h	%
250	A	3.42 (205)	133.7	11.8	35.67	12.6
	B	7.00 (420)	130.5	27.5	14.71	36.2
	C	6.50 (390)	120.6	11.9	16.72	7.2
	D	10.17 (610)	125.8	12.0	11.19	15.9
	E	2.58 (155)	83.8	11.3	28.08	7.2
	W	4.00 (240)	149.2	9.6	34.89	15.3
300	A	1.42 (85)	133.1	11.2	86.02	12.3
	B	6.50 (390)	128.1	11.6	17.92	42.7
	C	1.75 (105)	112.4	11.1	57.86	7.6
	D	1.67 (100)	118.6	11.6	64.17	18.8
	E	0.92 (55)	74.4	11.7	68.34	6.4
	W	1.50 (90)	151.1	10.3	93.89	14.7
350	A	1.00 (60)	127.7	9.4	118.34	10.8
	B	1.00 (60)	130.0	11.9	118.02	38.5
	C	1.00 (60)	121.2	11.8	109.39	7.6
	D	0.92 (55)	114.6	11.1	112.94	16.3
	E	0.58 (35)	76.1	12.1	109.67	6.4
	W	1.00 (60)	151.4	11.2	140.20	19.9

a/ 50 lb/in.^{2}

b/ $\frac{\text{Initial MC} - \text{Final MC}}{\text{Drying time}}$

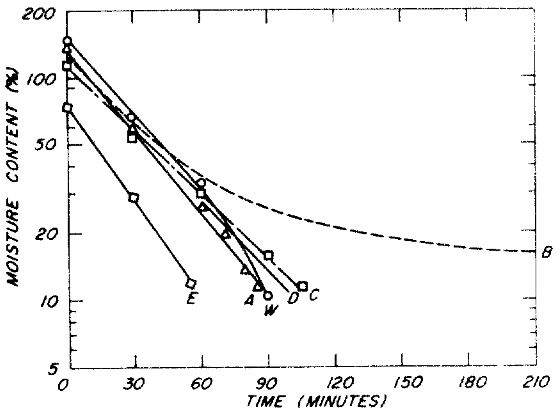

Fig. 9. Press drying curves of aspen plywood at 300°F.

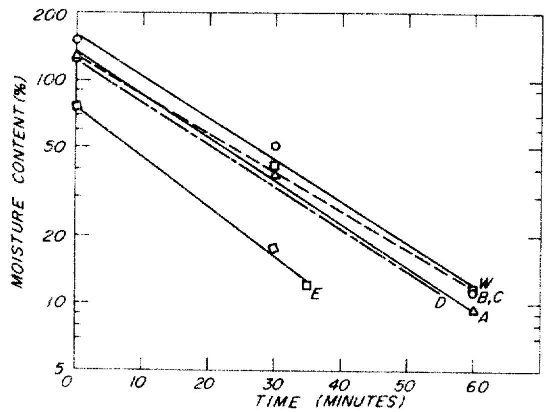

Fig. 10. Press drying curves of aspen plywood at 350°F.

Drying rates between species showed less variation than those among drying temperatures or treated types. Average drying rates for 5/8-inch-thick Douglas-fir plywood treated by the five different chemicals types and the water treatment were 23.0, 54.5, and 97.2% per hour at 250, 300, and 350°F, respectively. For aspen plywood the drying rates were 23.5, 64.7, and 118.1% per hour at the same temperatures. As a result, the increase in drying temperature increased the drying rate of treated aspen plywood more than it did treated Douglas-fir plywood.

The water- and chemical-treated plywoods (except B and E types) could be dried to 10 to 12% moisture content in 150 to 610 min. at 250°F, 80 to 115 min. at 300°F, and 55 to 70 min. at 350°F. B-type-treated plywood was shown to be very slow drying at 250 and 300°F, but it could be dried to the target moisture content in 95 min. in Douglas-fir and 60 min. in aspen at 350°F. E-type was dried very easily because the initial moisture content was distinctly lower than those of the other six treated types. This drying of FRT plywood is similar to the drying times cited by Hittmeier et al. (1968) even though the thicknesses of materials differed slightly.

Thickness shrinkage

Curves of the average shrinkage of the FRT and water-treated plywoods after drying (Fig. 11) show shrinkage of aspen plywood generally greater than that of Douglas-fir in all drying procedures. In conventional drying, the shrinkage of treated Douglas-fir and aspen plywood decreased slightly with an increase in drying temperature. High-temperature drying clearly increased shinkage with an increase of drying temperature. The same tendency appears in press drying with shrinkage of greater magnitude.

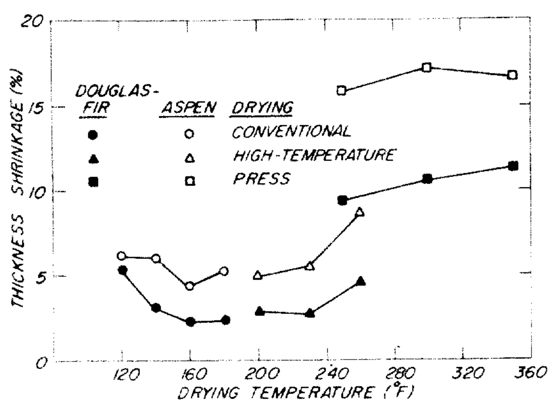

Fig. 11. Shrinkage comparison of Douglas-fir and aspen plywoods in conventional, high-temperature, and press drying.

Drying rate comparisons

Though drying data during the course of drying were not available for the FRT plywood, the mean drying rates (Tables 4 through 9) were converted to drying factors, K, to examine differences between drying methods. The shortcoming of doing this for the conventional kiln drying (because the dry- and wet-bulb temperatures were changed with time) was previously discussed.

Drying rate curves in terms of the factor K (per hour), a function of temperature, are plotted for 5/8-inch-thick treated Douglas-fir and aspen plywood (Figs. 12 through 15). Drying rate increases little with increasing temperature in conventional kiln drying, but increases dramatically at high temperatures (such as 230 or 260°F) (Fig. 12). The drying rates for treated plywood do vary more at the higher temperatures. Even greater drying rates are possible using the high temperatures of press drying (Fig. 13).

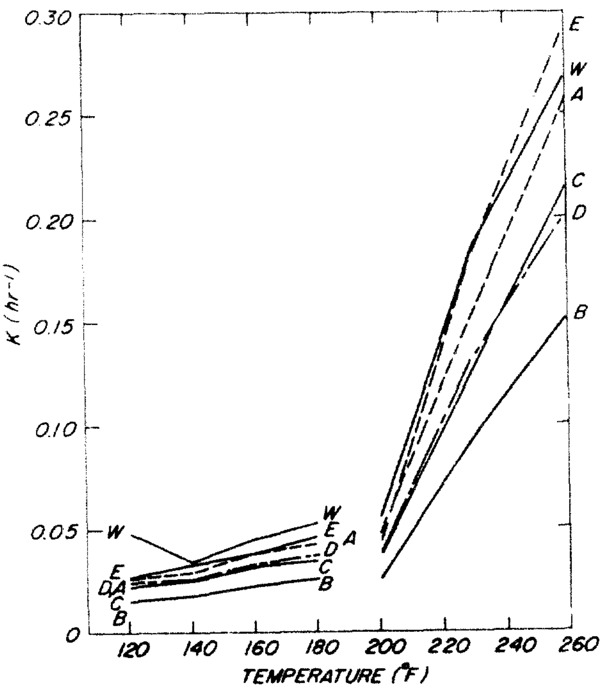

Fig. 12. Drying rate curves of Douglas fir plywood in conventional and high-temperature kiln drying.

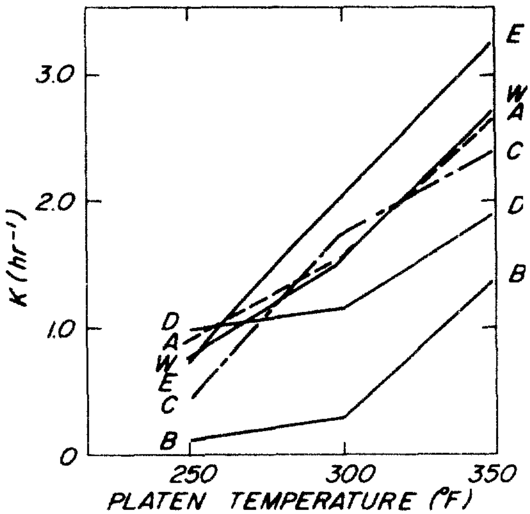

Fig. 13. Drying rate curves of Douglas-fir plywood in press drying.

Drying defects

Conventional and high-temperature kiln drying of treated Douglas-fir and aspen plywood generated drying defects (Table 10). The press-dried specimens were free of surface checking and warp. Wide surface checking was evident after conventional drying in Douglas-fir, but not in aspen. The most frequent warping defect for either conventional or high-temperature kiln drying was bowing. Twisting also sometimes appeared, but cupping did not. In comparing defect frequency between species, aspen plywood was observed to have a higher percentage of defects after conventional drying than was Douglas-fir plywood. As temperature increased, the percentage of defects increased in both. In general, the water-treated controls and the B-treated type were shown to have the greatest defect tendency among treated types, but there was little difference between the two species. Drying defects that appeared most frequently in high-temperature drying were medium surface checking and bowing in both Douglas-fir and aspen plywood. Accordingly, high-temperature drying generated more surface defects in treated plywood than did conventional drying.

Table 10. Drying defect severity and percentage specimens exhibiting defect

Plywood	Drying method	Surface checking		Twisting		Bowing	
		Specimens showing defect	Width of checks	Specimens showing defect	Deflection/ length	Specimens showing defect	Deflection/ length
		%	mm	%		%	
Douglas-fir							
	Conventional	100	[illegible]	4	<0.005	14	<0.005
	High-temperature	100	0.3-1.0	2	<0.005	13	<0.005
Aspen							
	Conventional	0	0	4	<0.005	21	0.005-0.010
	High-temperature	10	0.3-1.0	0	0	21	0.005-0.010

Treated plywoods changed color for some chemical treatments as a function of the drying process and species. Color change was not evident in water- and E-type-treated plywoods. However, B-type-treated plywoods darkened after drying to a light brownish-yellow. Press drying at 300°F or more produced a black color along with surface charring. D-type-treated plywoods also showed severe darkening, but in low-temperature drying the darkening was less severe than for B-type-treatments. A- and C-type-treated Douglas-fir plywoods changed to reddish yellow after drying and aspen to yellow in A and whitish yellow in C. HOwever, A- and C-type-treated plywoods only evidenced surface color change as compared with B and D which had darkened in depth.

CONCLUSIONS

This study examined the drying times, drying rates, and resulting drying defects for fire-retardant-treated 5/8-inch-thick exterior grade Douglas-fir plywood and aspen plywood. Drying methods were conventional kiln, high-temperature kiln and press drying.

In general, the results showed that the drying rates and qualities of B-type-treated (chromated zinc chloride) plywood were the poorest of the treatments evaluated. The C-type (minalith)- and D-type (pyresote)- treatment drying rates and qualities were better, but A-type (borax-boric acid) and E-type (commercial pyresote) treatments were best.

The relatively slow drying rate of the B-type-treated plywood as compared to the other treatments can be partially attributed to the surface effect of the salt on reducing the differential vapor pressure between the interior and plywood surface available for drying.

Conventional drying

Drying responses of treated plywoods in four runs of conventional drying were shown to differ with fire-retardant chemical type. In general, chemically treated plywoods had slower drying rates than did water-treated. Excluding the E-type-treated plywood, which differed in initial moisture content, A-type-treated plywood was most easily dried and B-type-treated was most difficult to dry of the five fire-retardant-chamical treatments. Drying times of all treated types, including water, were reduced with increasing temperature.

Drying defects increased with increasing temperature. The most frequently observed defects after conventional kiln drying were surface checking and bowing. Warping, also occurred but caution must be exercised in extending the warping of these relatively small unrestrained specimens (1- by 2- ft) to that of kiln-sized stock of 4- by 8-foot sheets of plywood.

Aspen had faster drying rates than did Douglas-fir for all the treated types (including water) at any drying temperature.

High-temperature drying

The drying rate response in high-temperature kiln drying was similar to that of conventional drying. However, an increase of drying temperature sharply reduced drying time and drying defects were more frequent.

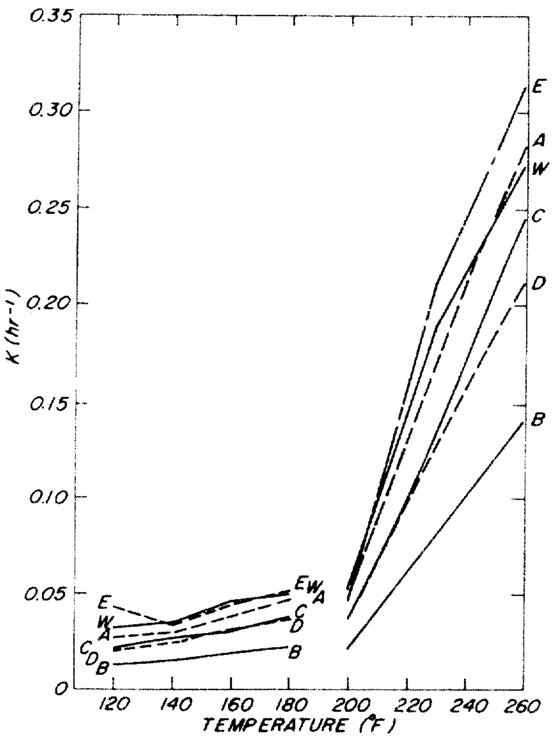

Fig. 14. Drying rate curves of aspen plywood in conventional and high-temperature kiln drying.

As with conventional drying, checking and bowing were common. Twisting did appear at times, and cupping seldom. B-type- and water-treated plywood had the greatest defect frequency and magnitude. Surface checking (0.3 to 1+ mm widths) was apparent in all specimens of Douglas-fir.

Press drying

Press drying rates were even greater than conventional and high-temperature kiln drying. However, thickness shrinkage increased several times as compared with those of conventional and high-temperature kiln drying. The B-type-treated plywoods of aspen were reduced one-third or more in thickness at 250, 300, and 350°F drying temperature.

Though the panels were free of surface checks and warp defects, some of the treated plywoods evidenced color change after drying. B- and D-type-treated plywoods were altered throughout to brown or brown-yellow in both Douglas-fir and aspen. The colors darkened more with an increase in drying temperature. A black color and charring of the surface was evident at 300°F or more in press drying.

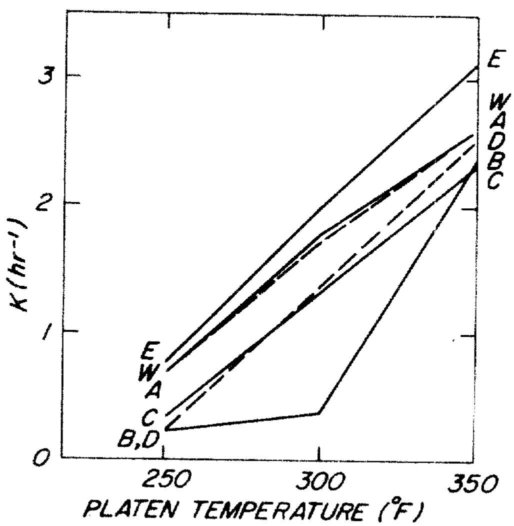

Fig. 15. Drying rate curves of aspen plywood in press drying.

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