FOCUS ARTICLE

EFFECTS OF REDRYING SCHEDULE ON PRESERVATIVE FIXATION AND STRENGTH OF CCA-TREATED LUMBER

R. SIDNEY BOONE
JERROLD E. WINANDY
JAMES J. FULLER

ABSTRACT

Southern pine and western hemlock dimension lumber specimens were pressure treated with chromated copper arsenate (CCA) and then redried using one of seven post-treatment schedules. The influences of these seven kiln- or air-drying schedules on chemical leachability, decay resistance, and wood strength were evaluated to better understand the relationship between the severity of the redrying process and CCA fixation. For southern pine, six kiln-drying schedules exhibited less leaching of chromium and arsenic than did CCA-treated material air-dried after treatment. Depending on the temperature in initial kiln-drying, chromium and arsenic leaching were significantly reduced after a two-step post-treatment kiln-redrying schedule having an initial 12-hour fixation and a small wet-bulb depression followed by a drying period. Further work is needed to optimize the fixation and drying period and the appropriate wet-bulb depression to ensure complete fixation. Leaching of copper in southern pine or chromium, copper, or arsenic in western hemlock was not affected by redrying schedules. No significant reduction in strength or decay resistance in southern pine or western hemlock lumber redried by any schedule was detected. Southern pine dimension lumber, which was initially kiln-dried at a high temperature and treated with CCA preservative, experienced a faster rate of redrying than did lumber initially kiln-dried at conventional temperature schedules.

To achieve an acceptable preservative treatment, southern pine and western hemlock lumber are usually dried to less than 19 and 25 percent moisture content (MC), respectively. When removed from the treating cylinder, treated lumber will have regained water and may have an MC between 50 and 100 percent. American Wood-Preservers' Association (AWPA) standards state that drying after treatment is required when dimensional stability, tightness of fit, and structural strength are critical to use (2). When post-treatment redrying is required, redried treated lumber must be reduced to ≤ 19 percent MC, thereby minimizing warp and surface checking (18). Kiln schedules currently used for commercial redrying of CCA-treated lumber appear to be adapted from schedules typically used for drying untreated lumber and poles from the green (i.e., unseasoned state) where the primary objective is the removal of water.

The problem is that redrying of CCA-treated lumber involves more than removing regained water from the wood and minimizing drying defects. When selecting redrying schedules, it is imperative that consideration be given to: 1) ensuring leach resistance of the preservative chemicals; 2) maintaining biological effectiveness; and 3) controlling reductions in strength properties.

Maximum dry-bulb temperature limits have been set to address concerns for loss of strength (24). However, the possible need for wet-bulb temperature limits and the adequacy of currently used redrying schedules to meet these considerations are a matter of some concern.

Fixation is a multiple-path chemical process of rendering the water-soluble preservative elements insoluble and, therefore, resistant to removal from the wood (11). Fixation is not fully understood, but is sometimes defined as the point when hexavalent chromium VI is no longer detectable and has primarily been reduced to chromium III (8,14). Complete reduction of the chromium indicates that the potential for copper and arsenic leaching has been minimized (10). This is of concern for long-

The authors are, respectively, Research Forest Products Technologist, Research Wood Scientist, and Research Wood Scientist, USDA Forest Serv., Forest Products Lab. (FPL), One Gifford Pinchot Dr., Madison, WI 53705-2398. The FPL is maintained in cooperation with the Univ. of Wisconsin. The use of trade or firm names in this publication is for reader information and does not imply endorsement by the USDA of any product or service. This paper was received for publication in September 1994.

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TABLE 1. — Experimental design.

Treatment		Redrying schedule (°F)[a]		Number of 6-ft. (1.8-m) boards[b]		
			Wet-bulb depression	Southern pine		Western hemlock
Redry	Preservative	Dry-bulb	(first 12 hr./ remaining time)	CT	HT	WH
1	CCA	140	5/25	11	16	8
2	CCA	140	10/25	11	16	8
3	CCA	140	25/25	11	16	8
4	CCA	165	10/25	11	16	8
5	CCA	165	20/35	11	16	8
6	CCA	165	35/35	11	16	8
7	CCA	Air-dry		11	16	8
8	Untreated			11	16	8

[a] °C = (°F – 32)/1.8. First/remaining indicates wet-bulb depression redrying temperature of first 12 hours and that of remaining hours.
[b] CT = conventional-temperature-dried southern pine; HT = high-temperature-dried southern pine; WH = western hemlock.

term bioefficacy, especially when preservative retention levels are set nearer minimum fungal-toxic thresholds. It has also become a health concern that can include issues such as ground water contamination, soil contamination, or direct skin contact with unfixed CCA.

The chemistry and physics of the fixation reactions of CCA in wood have been extensively studied (6,8-11,13-15,19,21). There seems to be general agreement that CCA will eventually fix; that is, the reaction will go to completion at ambient conditions of about 70°F (21°C) and relative humidity (RH) levels of 50 to 70 percent, requiring at least 4 days at these conditions. In cold areas, when the temperature approaches or falls below 32°F (0°C), fixation does not proceed (13,14). Even though adequate fixation may have occurred without redrying, water removal requirements have not been met.

A review of accelerated fixation of CCA-treated wood by Anderson (5) indicates that fixation can also be accomplished by hot water spray or bath, steam, and hot oil, as well as hot air or kiln-drying. There is evidence that drying at high temperatures can impede fixation and decrease bioefficacy (9). Gray (15) states that even minor changes in the treatment procedure (including accelerated drying and/or kiln-drying) can adversely affect biological performance and leachability of CCA. Rapid removal of free water during fixation is undesirable, because fixation reactions are essentially ionic. This can change the leaching characteristics and bioefficacy of treated wood (19). Surface MC of the wood was found to be a key parameter in determining the CCA fixation rate (6). In-service leachability of CCA is related to the temperature and MC of the wood during fixation (8); however, this relationship is not completely understood. Ruddick et al. (22) were recently granted a U.S. patent on a kiln-drying process intended to ensure fixation of CCA.

The objective of this exploratory study was to specifically relate the effect of seven post-treatment combinations of dry-bulb temperatures and wet-bulb depressions on CCA fixation to strength loss, aquatic leachability of the fixed preservative chemicals, and the bioefficacy of the redried treated product from CCA-treated southern pine and western hemlock lumber.

MATERIALS AND METHODS

EXPERIMENTAL MATERIAL

Both southern pine and western hemlock dimension lumber specimens were evaluated in this study. We acquired 131 flatsawn No. 1 southern pine 2 by 4's (actual 38 by 89 mm), 12 feet (3.7 m) long, from a sawmill in east central Mississippi (Neshoba County). This lumber had been initially kiln-dried to 19 percent MC or less and surfaced on four sides. Seventy-five 2 by 4's were from a kiln charge dried at high temperatures (maximum 280°F (137°C)), and fifty-six 2 by 4's were from a kiln charge dried at conventional kiln temperatures (maximum 190°F (88°C)). All stock was obtained from one mill to ensure the best uniformity of species and that logs were from similar sites.

A total of 70 western hemlock select structural 8-foot- (2.4-m-) long 2 by 4's were donated by the Western Wood Preserving Company in Sumner, Wash. The lumber was processed by a mill in the Puget Sound area from logs harvested on the Olympic Peninsula. Lumber was kiln-dried at a high-temperature schedule (maximum 235°F, 113°C) to 19 percent MC or less and surfaced on four sides.

Both groups of material were covered and transported to the USDA Forest Service, Forest Products Laboratory (FPL), in Madison, Wis. Upon arrival at the FPL, each 12-foot-long southern pine 2 by 4 was cross cut to produce two 6-foot- (1.8-m-) long boards, and a number was assigned to each board. Boards that had been initially dried at conventional kiln temperatures were kept separate and numbered to distinguish them from those that had been initially dried at high temperatures. A 6-foot board was cut from each 8-foot-long western hemlock 2 by 4, attempting to minimize knots in portions where bending specimens would be cut, and a number was assigned to each board.

SORTING

To ensure that approximately equal numbers of low, medium, and high strength levels were represented in each redrying group, the modulus of elasticity (MOE) of each 6-foot board was evaluated using transverse vibration. The MC of each 6-foot board was measured at three locations using a Wagner L-600 dielectric moisture meter. The average value of these three MC readings was recorded to the nearest 1 percent.

Based on MOE values from the transverse vibration evaluation, each of the three groups (high-tempcrature-dried southern pine, conventional-temperature-dried southern pine, and western hemlock) was separately sorted into eight redrying groups having matched MOE distributions **(Table 1).** The three untreated (control) groups were stacked on stickers in a conditioning room held at 74°F (23°C) and 65 percent RH.

WESTERN HEMLOCK INCISING

Hemlock lumber designated for preservative treatment is often incised when the lumber is green. Because our hemlock had been kiln-dried, we sub-

TABLE 2. — Treating schedules used for southern pine and western hemlock.

Species	Chemical	Initial vacuum	Pressure	Final vacuum
		(in.Hg @ 30 min.)	(MPa)	(in.Hg @ 15 min.)
Southern pine	CCA	>27	1.03 @ 60 min.	>27
Western hemlock	CCA	>27	0.86 @ 120 min.	>27
Western hemlock[a]	Water	>27	0.34 @ 60 min.	None

[a] Used to simulate green conditions prior to incising.

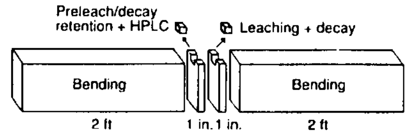

Figure 1.— Diagram of cutting pattern in the 6-foot (1.8-m) boards.

jected these 2 by 4's to a mild pressure treatment with water to simulate green lumber prior to incising **(Table 2).** Following this treatment, the hemlock 2 by 4's were held for 48 hours and then incised on the wide faces only, using the FPL incising machine with about 900 knife-like incisions/ft^2 (9600/m^2) to a depth of 0.2 inch (5 mm).

Preservative treatment

All boards, except controls, were pressure treated with CCA-C (oxide formulation) using a modified full-cell treatment to a target retention of 0.4 pcf (6.4 kg/m^3) at 0- to 0.6-inch (0- to 15-mm) assay zone. Southern pine and western hemlock treated with CCA required different treating schedules **(Table 2).**

The lumber was treated in 14 batches: 1 batch of southern pine having 2 sets (conventional and high temperature), and 1 batch of western hemlock per week for 7 weeks. After removal from the treating cylinder, the treated boards were close piled and held at room temperature (about 70°F) for 24 to 30 hours prior to loading in the dry kiln to simulate the 24 hours on the drip pad required in industry operations.

Redrying

Seven redrying schedules (six kiln and one air redried) were carried out. The choices of 165°F and 140°F (74°C and 60°C) as maximum dry-bulb temperatures for the study were based on previous work relating strength loss to maximum dry-bulb temperatures during redrying (23,25) and subsequent adoption of this information into the AWPA standards for redrying CCA-treated material. Three levels of wet-bulb depressions were selected for both dry-bulb temperatures to provide a range of redrying conditions—from rather slow initial drying to relatively severe initial drying. A small wet-bulb depression (slow initial drying) serves to keep the surface of the lumber wetter longer and provides favorable conditions for the fixation reactions to proceed (6). Large wet-bulb depressions in the initial stages of drying have traditionally been favored for minimal strength loss in the lumber. The wet-bulb depressions in this study were selected to give guidance for future studies on redrying CCA-treated lumber and are not currently viewed as final recommendations for industrial application. Similarly, the 12-hour time for the small wet-bulb depressions was arbitrarily selected to provide guidance for future studies and will likely need to be modified for industrial settings.

Study boards designed for kiln redrying were stacked in a steam-heated dry kiln. Stickers were 0.75 inch (19 mm) thick. Air velocity through the load averaged 500 ±100 feet/minute (2.5± 0.5 m/s). Because of the narrow load (about 8 to 9 in. (200 to 225 mm)), air-flow direction was not reversed during kiln runs.

A calculated ovendry weight of each board was determined at the start of drying based on the MC and air-dry weight of the board measured prior to preservative treatment. Each board was weighed when loaded in the kiln. All boards were weighed after 12 and 24 hours of drying. After 24 hours, boards were weighed again at 31, 48, 55, and 72 hours. Individual boards were removed from the kiln when the calculated MC was about 20 ±3 percent. Thus, drying time of each board varied.

Study boards designed for air redrying were stacked on 0.75-inch-thick stickers and stored inside the FPL treating plant (68°F (20°C) and 20% to 40% RH) for about 3 months until MC was 20 ±3 percent.

Following air or kiln redrying, boards were stacked on 0.75-inch-thick stickers in a conditioning room at 74°F and 65 percent RH (12% equilibrium MC) to equilibrate before further cutting into test specimens and blocks.

Testing and analyses

Following equilibration to 12 percent MC, each 6-foot board was cut into the four required specimens **(Fig. 1),** taking care to avoid knots. Specimens for the bending tests were 24 inches (610 mm) long and cut from nearer the ends. Two 1-inch- (25-mm-) long blocks were cut to provide material for decay resistance, leachability, and wood chemical component tests and to determine CCA retention levels.

Strength tests

Specimens were broken in flatwise bending using third-point loading. A rate of loading of 0.5 inch/minute (12.5 mm/min.) produced failure in 30 to 90 seconds. The test span was 22 inches (559 mm), yielding a span-to-depth ratio of 14.7 to 1. MOE, modulus of rupture (MOR), and work to maximum load (WML) were determined for each specimen from digitally recorded load and deflection data.

CCA retention levels

Prior to leaching and decay tests, preservative retention was determined after treatment for each board using atomic absorption spectrometry (3).

Wood chemical components tests

The small portion of material from the outer 0.75-inch zone of the first 1-inch-long specimen was ground to 30 mesh and divided. Half was analyzed for carbohydrates using high pressure liquid chromatography (20), and the remainder was analyzed for Klason lignin (12).

Leaching tests

Tests for the leachability of the three elements of the wood preservative were run using a modified AWPA E-11 test method (4). Modifications were made in block size and in time intervals when the leachates were collected. Blocks were 0.75 by 0.75 by 1 inch rather than the 0.75-inch cube stated in the E-11 standard. Collection and measurements for the leachate were set at 48- or 72-hour intervals, with exposure starting on

TABLE 3. — Preleach and predecay retention of CCA based on atomic absorption spectrometry.

Initial kiln-dry	Redrying schedule (°F)[a] Dry-bulb	Wet-bulb depression (first 12 hr./remaining time)	Retention Chromium	Copper	Arsenic
			------------ (%)	------------	
Southern pine (conventional temperature)	140	5/25	0.508	0.188	0.386
	140	10/25	0.440	0.176	0.345
	140	25/25	0.443	0.182	0.375
	165	10/35	0.467	0.183	0.379
	165	20/35	0.515	0.202	0.402
	165	35/35	0.473	0.189	0.381
	Air-dried		0.448	0.184	0.356
Southern pine (high temperature)	140	5/25	0.525	0.202	0.436
	140	10/25	0.519	0.200	0.411
	140	25/25	0.508	0.197	0.411
	165	10/35	0.495	0.187	0.406
	165	20/35	0.499	0.189	0.370
	165	35/35	0.481	0.189	0.367
	Air-dried		0.442	0.175	0.372
Western hemlock (high temperature)	140	5/25	0.405	0.164	0.367
	140	10/25	0.691	0.266	0.531
	140	25/25	0.491	0.185	0.402
	165	10/35	0.481	0.187	0.427
	165	20/35	0.435	0.169	0.379
	165	35/35	0.816	0.316	0.629
	Air-dried		0.402	0.160	0.366

[a] °C = (°F – 32)/1.8.

TABLE 4. — Percentage of boards redried to about 20 percent MC at various times.

Initial kiln-dry	Redry schedule (°F)[a] Dry-bulb	Wet-bulb depression (first 12 hr./remaining time)	Amount redried after 31 hr.	48 hr.	55 hr.	72 hr.
			------------ (%)			------------
Southern pine (conventional temperature)	140	5/25	--[b]	0	9	62
	140	10/25	--	9	36	82
	140	25/25	--	18	--	54
	165	10/35	0	27	54	100
	165	20/35	54	54	82	100
	165	35/35	9	54	91	100
Southern pine (high temperature)	140	5/25	--	50	87	100
	140	10/25	--	56	75	100
	140	25/25	--	69	--	100
	165	10/35	19	100	100	100
	165	20/35	69	100	100	100
	165	35/35	69	94	94	100
Western hemlock (high temperature)	140	5/25	--	12	38	87
	140	10/25	--	0	12	50
	140	25/25	--	0	--	62
	165	10/35	0	0	50	100
	165	20/35	0	12	62	100
	165	35/35	0	25	62	100

[a] °C = (°F – 32)/1.8.
[b] - - = no observations.

a Wednesday and leachate sample collection every Monday, Wednesday, or Friday, rather than the specified 48-hour intervals. The standard 14-day soak was used.

DECAY TESTS

Following leaching tests, those same blocks were air-dried at 74°F and 65 percent RH to 12 percent MC. Tests for decay resistance were run following ASTM-D 1413 (l), except a 0.75- by 0.75- by l-inch block was used. The usual 12-week exposure to the fungus was used. A brown-rot fungus, *Postia placenta* (MAD 698), was selected for the decay test because it is a recognized copper-tolerant species and very aggressive and virulent against most softwoods, particularly southern pine.

RESULTS AND DISCUSSION

CCA RETENTION

The target retention for both southern pine and western hemlock was 0.40 pcf. Calculated retention levels based on weight gain averaged 0.408 pcf (6.5 kg/m^3) for southern pine and 0.390 pcf (6.2 kg/m^3) for western hemlock. Preservative retention based on results of atomic absorption spectrometry of 0.75-inch-deep assay blocks are shown in **Table 3.** Southern pine sapwood was completely penetrated, but that in western hemlock was generally less than the required 0.4 inch (10 mm), with CCA penetration averaging about 0.3 inch (7.6 mm). This reduced penetration was directly attributable to the 0.2-inch incising depth used.

REDRYING TIMES

In this study we used two groups of southern pine, one initially dried at conventional temperature and one initially dried at high temperature. In all kiln-redrying schedules, the southern pine boards initially dried at high temperature dried faster during redrying after CCA treatment than did the boards initially dried at conventional temperatures **(Table 4).** We previously observed that lumber initially kiln-dried at high temperature (235°F to 280°F) dried at a faster rate when redried than did lumber that was initially kiln-dried at conventional temperatures (maximum 190°F (25)). These drying times related to redrying dry-bulb temperatures and especially wet-bulb depressions suggest that different drying times will be required to redry treated lumber to any given level of MC, depending on the initial kiln-drying temperature used.

Western hemlock, which was initially high-temperature dried, had redrying times similar to southern pine that was initially dried at conventional temperatures.

Strength properties

Significant changes in MOE, MOR, or WML were not attributable to any redrying schedule **(Table 5).** The somewhat higher value for MOR in the untreated hemlock (control) was probably because it was not incised. All preservative-treated western hemlock was incised, which is customary in industrial practice.

Drying wood in a high-RH environment can result in an accelerated strength loss in wood if this environment is too severe for too long. Conversely, the chemical fixation rate of CCA is enhanced by keeping the surface of the wood from drying too rapidly. In kiln-drying, these conflicting issues are controlled by the wet-bulb depression temperature. When adjustments in wet-bulb depressions and/or length of the period are made to achieve adequate chemical fixation in future research or in scale-up for industrial application, concern for possible strength loss should not be dismissed.

Chemical composition

High pressure liquid chronographic results indicated no change in the percentage of Klason- and acid-soluble lignin content for southern pine or western hemlock in response to any redrying schedule **(Table 6).** Results also indicated no change in the percentage of carbohydrate content (arabinan, galactan, glucan, mannan, xylan). This is consistent with previous results where chemical composition was a good indicator of strength loss or lack thereof (17,26).

CCA leachability

Our results confirm that the quantities of chromium, copper, and arsenic that leach from CCA-treated wood are closely tied to the systematic progression of multiple oxidation-reduction reactions during the chemical fixation process and the redrying schedule used during those reactions. The cumulative leached chromium, copper, and arsenic elements are shown in **Figure 2.** There were significant differences ($\alpha \leq 0.05$) in the cumulative leaching of chromium and arsenic among the drying/fixation schedules for both groups of southern pine initially dried at conventional temperatures or initially dried at high temperatures **(Table 7).** For chromium, the least amount of leaching occurred in the redrying schedule with the lowest dry-bulb temperature (140°F) and smallest wet-bulb depression (5°F, 3°C)). With few exceptions, leachability of chromium from kiln-dried CCA-treated

TABLE 5. — Properties by species and redrying schedule.[a]

Initial kiln-dry	Redrying schedule (°F) Dry-bulb	Redrying schedule (°F) Wet-bulb depression (first 12 hr./ remaining time)	Property MOE	Property MOR	Property WML	Property MC	Property Specific gravity[b]
			(psi × 10^3)	(psi)	(in.-lb./in.^{3})	(%)	
Southern pine (conventional temperature)							
CCA	140	5/25	1,963	10,780	9.6	12.2	0.61
	140	10/25	1,986	11,140	10.8	12.0	0.63
	140	25/25	1,956	10,680	9.2	12.4	0.62
	165	10/35	1,950	11,080	10.5	11.9	0.62
	165	20/35	1,990	10,870	9.9	12.0	0.61
	165	35/35	1,980	11,090	10.4	11.2	0.60
	Air-dried		2,140	11,070	10.1	11.6	0.61
Control	None		2,090	11,380	11.0	10.5	0.57
Southern pine (high temperature)							
CCA	140	5/25	2,020	10,850	10.0	12.3	0.61
	140	10/25	1,870	10,630	10.6	12.4	0.60
	140	25/25	2,030	10,630	9.4	12.6	0.61
	165	10/35	2,030	10,870	10.4	12.1	0.59
	165	20/35	2,060	11,040	10.1	12.6	0.62
	165	35/35	1,930	10,770	11.2	12.0	0.60
	Air-dried		2,060	11,230	10.6	11.5	0.59
Control	None		2,000	11,350	11.4	10.4	0.59
Western hemlock							
CCA	140	5/25	1,480	7,330	6.1	12.1	0.49
	140	10/25	1,440	6,740	5.0	12.7	0.45
	140	25/25	1,470	6,720	4.4	12.4	0.48
	165	10/35	1,770	6,780	4.8	12.0	0.46
	165	20/35	1,490	7,130	5.5	12.4	0.44
	165	35/35	1,920	6,160	3.5	11.8	0.44
	Air-dried		1,540	7,440	4.6	11.6	0.48
Control	None		1,530	8,530	8.8	11.8	0.46

[a] °C = (°F − 32)/1.8; 1 psi = 6,894 Pa; 1 in.-lb./in.^{3} = 6.895 kJ/m^3.
[b] Ovendry weight/volume at measured MC (not corrected for weight of CCA).

TABLE 6. — Percentage (by weight) of lignin and wood sugars by redrying treatment and species group.

	Redrying schedule (°F)[a]		Lignin		Chemical composition					
Initial kiln-dry	Dry-bulb	Wet-bulb depression (first 12 hr./ remaining time)	Kraft	Acid-soluble	Arabinan	Galactan	Glucan	Xylan	Mannan	Total
			(%)							
Southern pine (conventional temperature)										
CCA	140	5/25	28.0	0.8	0.98	1.47	43.34	5.43	11.54	91.4
	140	10/25	29.0	0.6	1.01	1.93	43.98	5.48	11.29	93.2
	140	25/25	28.9	0.5	1.03	2.09	44.33	5.33	10.92	93.6
	165	10/35	29.2	0.5	1.03	1.97	44.42	5.89	11.32	94.4
	165	20/35	29.5	0.5	1.04	2.29	46.23	5.72	11.71	97.0
	165	35/35	28.7	0.5	0.99	1.66	43.76	5.28	11.82	92.7
	Air-dried		29.1	0.6	1.05	1.77	43.41	5.62	11.22	92.7
Control	None		29.0	0.3	1.07	1.51	44.19	5.43	11.72	93.2
Southern pine (high temperature)										
CCA	140	5/25	29.5	0.5	0.95	1.99	42.99	5.81	11.09	92.9
	140	10/25	28.9	0.4	0.95	2.04	43.02	5.54	11.27	92.1
	140	25/25	29.3	0.5	0.97	2.10	43.39	5.68	11.19	93.1
	165	10/35	28.8	0.4	0.92	2.00	43.29	5.59	10.86	91.9
	165	20/35	30.2	0.5	0.97	2.79	42.67	5.74	11.07	93.9
	165	35/35	29.5	0.5	1.09	2.26	45.55	5.95	11.89	96.7
	Air-dried		29.1	0.5	1.02	2.05	44.23	5.82	11.46	94.2
Control	None		29.1	0.3	1.16	1.99	43.35	5.93	11.92	95.8
Western hemlock										
CCA	140	5/25	30.5	0.5	0.77	1.88	45.43	3.46	13.31	95.8
	140	10/25	31.4	0.4	0.79	1.71	46.86	3.44	13.28	97.8
	140	25/25	30.9	0.4	0.80	1.89	46.19	3.45	13.18	96.8
	165	10/35	30.6	0.4	0.82	1.83	45.69	3.66	13.66	96.6
	165	20/35	29.8	0.3	0.80	1.51	47.68	3.66	14.11	97.9
	165	35/35	30.0	0.4	0.84	1.72	46.09	3.50	14.46	97.0
	Air-dried		29.6	0.4	0.77	1.87	45.02	3.30	13.58	94.6
Control	None		31.3	0.2	0.81	2.56	47.56	3.52	13.19	99.1

[a] °C = (°F − 32)/1.8.

southern pine progressively increased as dry-bulb temperature and wet-bulb depression increased. The most leaching of chromium occurred when CCA-treated material was air-dried (68°F) at low RH.

The same significant ($\alpha \leq 0.05$) trend is apparent in the leaching of arsenic. The least amount leached with the mildest dry-bulb temperature and the smallest wet-bulb depression, and the most amount leached when CCA was air-dried at low RH **(Table 7).** Again, arsenic leachability generally increased as dry-bulb temperature and wet-bulb depression increased. These data clearly show that redrying schedules that do not promote excessive moisture loss during the initial hours of fixation provide superior resistance to leaching.

An analysis of variance (ANOVA) indicated no significant difference in the leaching of copper for either group of southern pine **(Table 7).**

An ANOVA indicated that no significant difference existed in the leaching of chromium, arsenic, or copper in western hemlock with any redrying schedule **(Table 7).** The most probable cause for hemlock not showing the same trends as southern pine is that the variation in penetration and retention levels within groups was large.

For southern pine, the rate of leaching of chromium and arsenic are shown in **Figure 3.** Note that the general rate of leaching for chromium or arsenic seemed to be a function of that redry

TABLE 7. — Analysis of variance of cumulative CCA elements leached with results of Duncan's Multiple Range Test of cumulative leaching shown in footnotes.[a]

Species group	Initial kiln-dry	Arsenic	Chromium	Copper
	(°F)			
Southern pine	190	*[b]	*[d]	NS
Southern pine	235	*[c]	*[e]	NS
Western hemlock	235	NS	NS	NS

[a] NS = not significant ($\alpha < 0.05$); °C = (°F − 32)/1.8.
In the following footnotes, kiln redrying schedules are denoted by [dry-bulb temperature]/[wet-bulb depression first 12 hr.]. Kiln redrying schedules are listed from most element leached (left) to least element leached (right); underlining indicates schedules having no significant difference ($\alpha < 0.05$).

[b] Air-dry 165/25 165/10 165/35 140/25 140/10 140/5

[c] Air-dry 140/25 165/35 165/10 165/25 140/10 140/5

[d] 165/35 Air-dry 165/10 140/10 140/25 165/25 140/5

[e] Air-dry 140/25 165/10 165/25 165/35 140/10 140/5

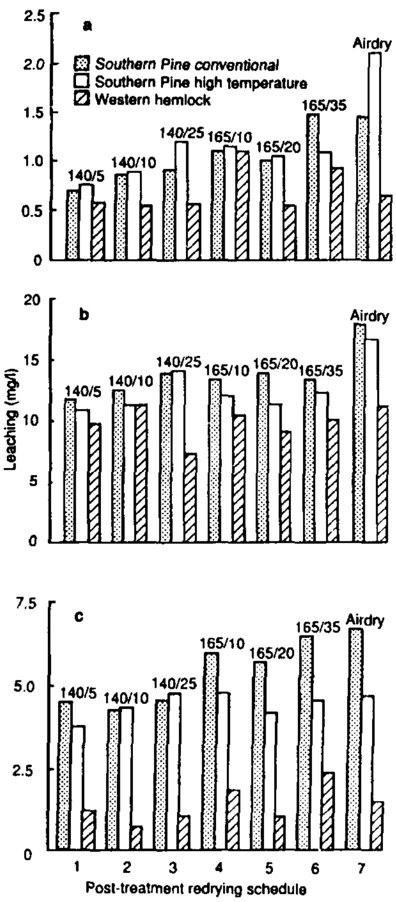

Figure 2. — Total cumulative leaching by redrying schedule (defined as dry-bulb/wet-bulb depression temperatures) and species group: a) chromium; b) arsenic; c) copper.

schedule's potential to avoid initial quick loss of moisture. The rate of leaching was lowest in the redrying schedule with the lowest dry-bulb temperature (140°F) and the smallest wet-bulb depression (5°F). With few exceptions, the rate of leaching for chromium in either initial kiln-drying group studied progressively increased as dry-bulb temperature and wet-bulb depression increased **(Fig. 3a,b).** The greatest rate of leaching for chromium occurred when CCA-treated material was air-dried (68°F) with no wet-bulb control **(Fig. 3a,b).**

The same general trend was apparent in the rate of leaching for arsenic. The least amount leached with the mildest dry-bulb temperature and the smallest wet-bulb depression, and the most amount leached when CCA was air-

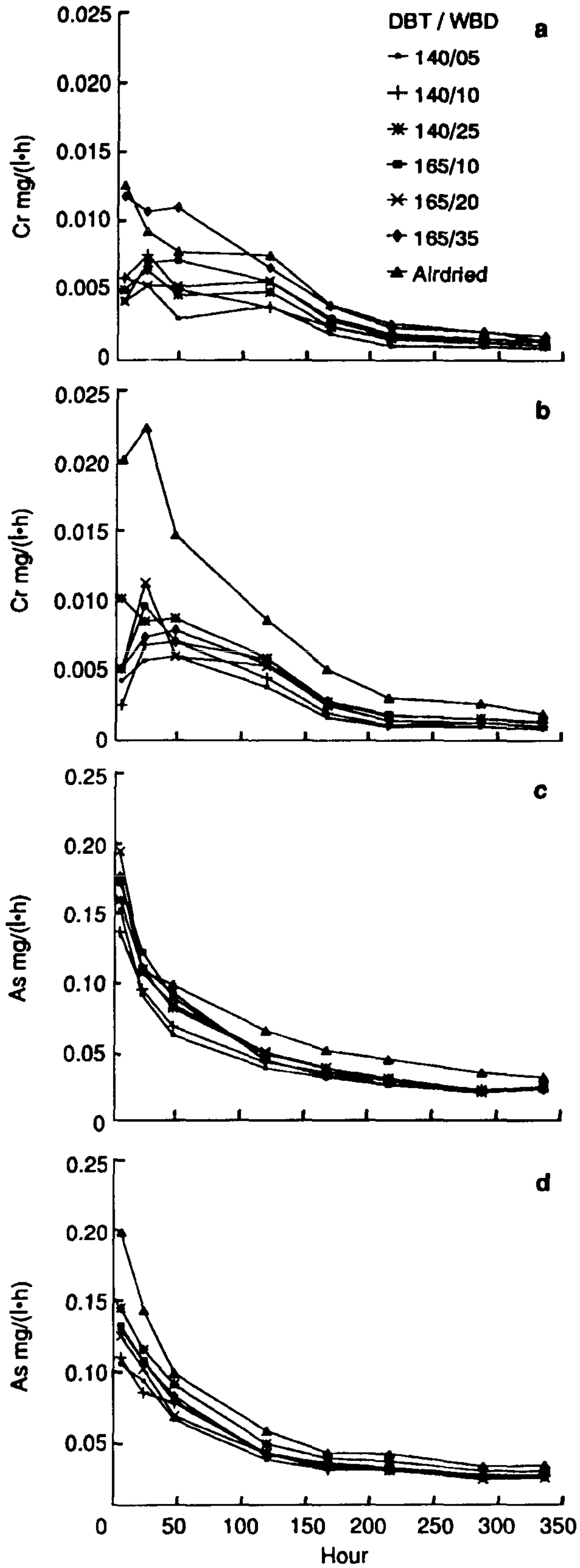

Figure 3. — Rate of leaching by redrying treatment and species group: a) southern pine—conventional kiln dried (chromium); b) southern pine—high-temperature kiln-dried (chromium); c) southern pine—conventional-temperature kiln-dried (arsenic); d) southern pine—high-temperature kiln-dried (arsenic).

dried after treatment **(Fig. 3c,d).** Again, arsenic leachability generally increased as dry-bulb temperature and wet-bulb depression increased.

Overall, the rate of leaching data showed that the tendency for chromium and arsenic to leach from southern pine was consistent during the 14-day leaching exposure. This shows that the cumulative leach data were not biased by an early single observation or trend. As such, the rate of leaching data confirms the results of the aforementioned statistical analysis in that fixation is enhanced by early control of wet-bulb depression to ensure adequate moisture to catalyze the fixation reactions.

Our results differ from Lee's (16), who found that air-redried material experienced less chromium, copper, and arsenic leaching than did material kiln redried at dry-bulb temperatures of 140°F or 180°F (60°C or 82°C). However, differences in the two experiments and redrying techniques may explain the differences in the results. The 1- by 1- by 9-inch specimens used by Lee (16) were quickly dried to 20 ±5 percent MC (21 hr. at 140°F and 9 hr. at 180°F), then placed in heat-resistant bags, and heated for 7 days at 140°F and 4 days at 180°F. This attempt to simulate kiln-drying was developed for drying small, clear specimens to evaluate strength properties (7). It allows little control of the initial rate of drying and was shown in both these studies to be a significant factor on the leachability of chromium and arsenic. We believe that our method of treating and redrying full-size lumber is more representative of expected fixation of treated lumber exposed to leaching in-service.

Based on our results, we propose that better resistance to chromium and arsenic leaching from CCA-treated southern pine lumber is obtained using a moderate kiln-redrying dry-bulb temperature with a short controlled fixation period and a high RH rather than a drying schedule containing a low RH.

Decay resistance (bioefficacy)

Following leaching tests, each 0.75- by 0.75- by 1.0-inch sample was exposed to decay fungi following techniques outlined in ASTM 1413 (1). Inspection of the blocks when placing them in the bottles indicated that southern pine specimens had full preservative penetration, but in western hemlock specimens, penetration was variable, with some western hemlock heartwood areas untreated, even though the stock was incised. This variability made it difficult to interpret the soil block results.

The brown-rot fungus *(Postia placenta* MAD 698) quickly established itself on the untreated controls. After the 12-week exposure, *Postia placenta* had induced between 40 and 60 percent weight loss in untreated southern pine and western hemlock controls. We noted no significant influence in decay resistance among the seven redrying schedules in either group of CCA-treated southern pine (all < 5% weight loss). However, the use of CCA retention levels closer to the toxic threshold of CCA rather than AWPA-specified retention levels, which are nearly double toxic thresholds, may have increased sensitivity and altered the results.

A visual inspection of the decayed western hemlock soil block specimens showed that decay from *P. placenta* on CCA-treated western hemlock was virtually complete throughout the unpenetrated sections, but unnoticeable in the treated portion of each block. Because of variable penetration of CCA-treated blocks in western hemlock, wc do not feel that the results of the hemlock soil block test were a conclusive indicator of the effects of redrying schedule on bioefficacy and therefore they have not been reported.

Conclusions

This study demonstrates that preservative-treated lumber using kiln redrying schedules employing small, controlled wet-bulb depression temperatures can maintain adequate moisture for fixation reactions to finalize. Such schedules significantly reduced leaching of arsenic in southern pine lumber when compared with faster kiln-drying schedules having large wet-bulb depressions. Most kiln-redrying schedules significantly reduced leaching of chromium and arsenic when compared with am-drying after treatment at 70°F. The drying temperature (conventional or high) used to initially kiln-dry the untreated lumber was also found to be an important variable in chromium and arsenic leaching. None of the redry schedules studied significantly influenced the leaching of copper from CCA-treated southern pine or the leaching of chromium, copper, or arsenic from CCA-treated western hemlock. Additional work is needed to better define optimum wet-bulb depression and length of fixation for southern pine and western hemlock lumber.

The mechanical properties (MOR, MOE, and WML), chemical composition, and decay resistance of CCA-treated southern pine and western hemlock lumber were not significantly affected by the redrying schedules used in this study.

Southern pine lumber initially kiln dried at high temperatures (>235°F) redried at a faster rate after CCA treatment than did lumber initially kiln-dried at conventional temperatures (maximum 180°F to 190°F).

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