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The Moisture-Excluding Effectiveness of Finishes on Wood Surfaces

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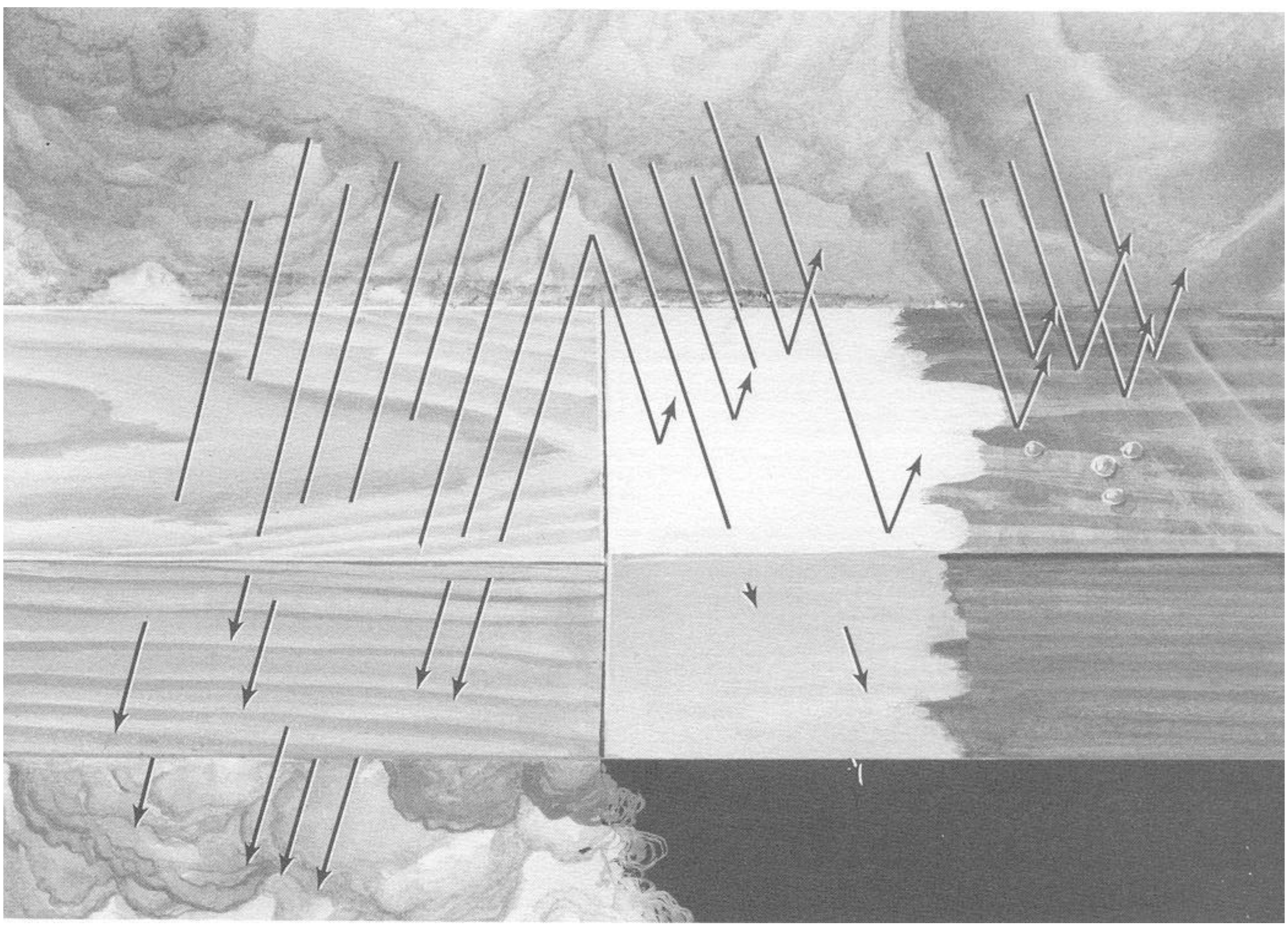

Abstract

Permeability to water vapor is one of the more important properties affecting the performance of coatings and other wood finishes. Often, one of the main purposes of finishing wood is to restrict moisture movement from the surroundings. We evaluated the moisture-excluding effectiveness (MEE) of 91 finishes on ponderosa pine sapwood, using the Forest Products Laboratory method in which finished and unfinished wood specimens in equilibrium with 30 percent relative humidity (RH) at 80 °F are weighed before and after exposure to 90 percent RH at 80 °F.

Finishes with the best MEE were pigmented, nonaqueous (solvent-borne) finishes. Two-component epoxy paint systems had MEE values greater than 85 percent after 14 days when three coats were put on the wood. Molten paraffin wax and a sheathing grade, two-component epoxy material with no solvent were the very best finishes found in this study for controlling moisture vapor movement into wood. The MEE is a direct function of the number of coats of finish applied to the wood (film thickness) and the length of time of exposure to a particular humidity. Only 11 finishes were found to retard moisture vapor movement into wood with any degree of success over the relatively short time of 14 days, and then only when two or three coats were applied.

These studies include evaluations of MEE by finish type, number of coats, substrate type, sample size, and time of exposure, and describe the effect on MEE of repeated adsorption/desorption cycles.

This paper should be useful to builders, architects, wood furniture manufacturers, those who make wood finish formulations, and anyone else interested in controlling water vapor movement into or out of wood. The information will benefit those who need to select wood finishes with specific moisture-excluding effectiveness.

Keywords: Water vapor, moisture exclusion, paints, coatings, wood finishes, adsorption, desorption.

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Errata

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The two figures on page 37 are reversed. That is, the figure shown with the caption labeled "Figure 11" should be with the caption labeled "Figure 12," and the figure shown with the caption labeled "Figure 12" should be with the caption labeled "Figure 11."

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The Moisture-Excluding Effectiveness of Finishes on Wood Surfaces

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The primary objective of the work reported here was to measure the moisture-excluding effectiveness of a wide range of commercially available surface treatments and finishes on wood. We studied the important variables of film thickness, wood species and substrates (plywood, hardboard, flakeboard, etc.), and time. Our studies were restricted to the measurement of the effectiveness of finishes on wood against water vapor between 30 and 90 percent relative humidity (RH) at 80 °F.

Data in the tables and Appendices of this report have been condensed as far as possible for the convenience of the reader. Complete data and descriptions of the finishes used can be obtained by contacting the U.S. Department of Commerce, National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161 (phone: (703) 487-4650 or (703) 487-4700 (RUSH)). The information is listed with NTIS by the same authors under the title: 'The moisture-excluding effectiveness of finishes on wood surfaces-support data"(*8*).[a]

Water is a prime factor in the environment of many finished products and permeability to water (as liquid or vapor) is therefore a property of major importance in most finish applications, protective or decorative. With metal substrates, the usual aim in applying a coating (finish) is to protect against wet corrosion; with masonry and other porous inorganic structures, coatings are applied to minimize water seepage and "breathing" of moisture vapor; with wood substrates, the protective function of coatings and other finishes is to minimize deterioration of the underlying structure by the combined action of moisture, sunlight, oxygen and microorganisms.

Moisture affects the shrinking and swelling of wood (*22,25*); a coating on wood therefore serves a desirable function if it controls moisture sorption by the wood. Although paints and other coatings (hereafter called finishes) have many other important functions and properties, an understanding of the moisture-excluding effectiveness (MEE) of finishes and its measurement is essential because of the importance of dimensional stability to many wood applications, both indoors and outdoors.

[a]Italicized numbers in parentheses refer to literature cited at the end of this report.

Earlier Work

It has long been recognized that coatings of paint and other finishes can prevent rapid changes in the moisture content (MC) of wood (*3,4,12,22,26,27*). The ability of finishes to protect wood against weathering depends partly upon the property of moisture exclusion (*6,7,11,15,18,19,23*). Moisture exclusion is also a valuable property of many interior finishes for wood (*1,10,14,26*).

Michaels (*14*) has shown that in homogeneous polymers (such as paint resins), water permeability is governed by the concurrent processes of water adsorption and diffusion, which are determined by the polarity of the polymer, and such polymer structural features as chain-stiffness, crystallinity, and cross-link density. Low-polarity polymers of high crystallinity, stiffness, and/or cross-linkage are the best water-barriers. Fillers and pigments added to the polymer films (i.e. paints) can significantly improve water-barrier properties when the particles are properly dispersed and of suitable size and shape. With latex-derived coatings, moisture permeability is often high and is affected by the composition and concentration of surfactants and stabilizers in the latex.

Various methods are used to evaluate the moisture permeability of finishes. Some methods use isolated films (*1,5,10,14,28-30*). Others apply the finish directly to wood (*3,4,12,15-21,23,24*). The Forest Products Laboratory (FPL) method used in early investigations of moisture-proof finishes (*3,4,12,25*) measured the moisture (water vapor) gain of wood protected on all sides by the finish and exposed to a controlled atmosphere of high humidity.

Evaluation Method

We used the FPL method in the studies reported in this paper because it represents a "real world" situation under non-steady-state conditions. The finishes to be evaluated were applied by brush to selected specimens of clear ponderosa pine (*Pinus ponderosa*) sapwood measuring 3 x 5 x 5/8 in. (tangential x longitudinal x radial dimensions), and having carefully rounded edges and corners (fig. 1). Three replicates were used. The specimens were conditioned to 30 percent RH at 80 °F, finished with the appropriate material, dried, and reconditioned at 30 percent RH and 80 °F to equilibrium. The specimens were then weighed and exposed to 90 percent RH and 80 °F for various time periods. Each finished specimen was accompanied by an end-matched, uncoated control conditioned and handled in exactly the same way. All specimens were weighed at appropriate intervals (1,7,14, 21 days and longer as needed). Complete experimental details and methods are shown in the Test Procedures, Materials, Methods section at the end of this publication. Additional studies were conducted on other wood substrates.

Moisture-Excluding Effectiveness (MEE)

The amount of moisture vapor passing through the finishes and adsorbed by the wood was determined from the gain in weight of the sample between 30 and 90 percent RH after different intervals of exposure. The MEE against water vapor for the various finishes was calculated by comparison with the weight of moisture adsorbed by the uncoated panels (*3,4*):

$$MEE = \frac{U - C}{U} \times 100$$

where U = weight of moisture adsorbed by uncoated wood
C = weight of moisture adsorbed by finished wood.

Measurements are readily made by this method with a good degree of accuracy. Furthermore, the experimental conditions are such that the results express the combined effect of the permeability of the finish and the adsorption characteristics of the wood. However, even with careful selection of the wood specimens, the possibility of natural variation in wood structure and adsorption characteristics is not removed. Variations in the adsorption characteristics of the wood may not seriously affect the amounts of moisture adsorbed by the finished specimens, but they do seriously affect the MEE values. This is because MEE values are based on the amount of moisture adsorbed by the uncoated wood, and different bare wood specimens (the controls) adsorb different amounts of moisture. This aspect of the test is discussed in detail in the section entitled Effect of Density of the Wood Specimen.

A further difficulty is that the conditions of the test for MEE are empirical. As the wood approaches its fiber saturation point the rate of diffusion of moisture through the finish decreases (20,22), so that the longer the exposure to high humidity, the lower is the apparent MEE of the finish. The countervailing advantages of the test are that it does represent service conditions of finished wood and does reflect the degree of interaction between the substrate and the finish and any stresses placed on the finish as the wood expands during wetting.

Finishes

For these studies we selected a wide range of commercially available finishes and several laboratory prepared finishes whose descriptions and compositions are summarized in Appendices A and B, and given in detail in (*8*). For convenience we grouped the selected finishes under a descriptive classification based on the suggested use and composition of the finishes (interior/exterior/combination, pigmented/unpigmented and aqueous/nonaqueous) as set out in Appendix A. The finishes were applied by brush. From one to six coats were applied to the conditioned wood surface. Several finishes were used in combinations.

MEE of Finishes on Standard Wood Specimens

The MEE of the finishes selected for this study were determined for one, two, and three coats of each finish on ponderosa pine clear sapwood between 30 and 90 percent RH at 80 °F (table 1 and (*8*)). Values were determined after 1, 7, and 14 days. The test for MEE was continued beyond 14 days until the observed value fell below 50 percent. Since MEE changes with time, all MEE values are discussed in terms of the day of measurement (e.g. MEE_{14}, stands for the measurement at 14 days) and, unless specified otherwise, are the average of three determinations.

Figure 1.—Ponderosa pine test specimen pairs in exposure rack.

Table 1.—Moisture–excluding effectiveness (MEE_t) of finishes on ponderosa pine sapwood (after t days exposure at 90 pct relative humidity, average of three replicates)

Finish[a]	Number of coats	Coverage			Wood density	MEE_t for—						
		1 coat	2 coats	3 coats		t=1	t=7	t=14	t=21	t=28	t=35	t=60
		Ft^2/gal			Lb/ft^3	Pct						
		EXTERIOR, UNPIGMENTED, NONAQUEOUS FINISHES										
1	1	303	—	—	24.8	48	6	−0	—	—	—	—
1	2	304	494	—	24.6	90	66	46	—	—	—	—
1	3	303	517	510	24.9	94	81	66	58	47	—	—
2	1	408	—	—	24.9	13	−0	−2	—	—	—	—
3	1	436	—	—	23.0	12	−0	−1	—	—	—	—
3	2	433	679	—	23.4	46	2	−1	—	—	—	—
3	3	408	729	868	21.5	78	27	11	—	—	—	—
4	1	320	—	—	22.9	59	13	3	—	—	—	—
4	2	317	327	—	22.9	81	38	17	—	—	—	—
4	3	287	324	345	22.7	88	51	29	—	—	—	—
		COMBINATION EXTERIOR/INTERIOR, UNPIGMENTED, NONAQUEOUS FINISHES										
5	1	302	—	—	24.9	71	8	3	—	—	—	—
5	2	325	265	—	24.6	90	36	2	—	—	—	—
5	3	317	255	261	24.5	94	60	16	—	—	—	—
6	1	256	—	—	26.1	93	73	54	40	—	—	—
6	2	247	444	—	26.2	98	93	88	83	79	74	61
6	3	346	422	387	27.7	98	95	91	88	84	81	70
7	1	552	—	—	23.9	45	4	−1	—	—	—	—
7	2	546	791	—	23.5	79	32	15	—	—	—	—
7	3	526	789	948	23.8	87	51	31	—	—	—	—
8	1	529	—	—	22.2	34	0	−1	—	—	—	—
8	2	547	778	—	22.7	46	2	−1	—	—	—	—
8	3	580	750	844	22.8	52	6	2	—	—	—	—
9	1	325	—	—	24.5	58	10	2	—	—	—	—
9	2	349	497	—	24.6	87	53	33	—	—	—	—
9	3	354	537	400	25.4	95	78	63	52	—	—	—
10	1	355	—	—	25.2	28	1	−0	—	—	—	—
10	2	357	497	—	25.6	64	19	6	—	—	—	—
10	3	341	473	438	25.6	85	51	29	—	—	—	—
11	1	392	—	—	22.4	12	−4	−5	—	—	—	—
11	2	423	579	—	22.5	22	−2	−4	—	—	—	—
11	3	532	603	872	24.1	33	2	−0	—	—	—	—
12	1	561	—	—	25.3	7	−1	−1	—	—	—	—
12	2	546	803	—	25.6	15	2	1	—	—	—	—
12	3	514	649	768	25.6	18	0	−1	—	—	—	—
13	1	505	—	—	24.5	55	10	2	—	—	—	—
13	2	507	635	—	24.5	83	43	23	—	—	—	—
13	3	497	580	559	25.2	89	64	44	—	—	—	—
14	1	554	—	—	26.2	48	6	0	—	—	—	—
14	2	573	867	—	25.9	80	36	15	—	—	—	—
14	3	539	884	776	26.3	87	53	30	—	—	—	—
15	1	526	—	—	25.3	60	24	11	—	—	—	—
15	2	547	741	—	25.2	87	56	36	—	—	—	—
15	3	575	744	1016	24.5	89	63	44	—	—	—	—
16	1	518	—	—	24.7	56	11	2	—	—	—	—
16	2	545	626	—	24.6	84	46	27	—	—	—	—
16	3	570	635	936	24.5	88	58	37	—	—	—	—

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Table 1.—Moisture–excluding effectiveness (MEE_t) of finishes on ponderosa pine sapwood (after t days exposure at 90 pct relative humidity, average of three replicates)–con.

Finish[a]	Number of coats	Coverage 1 coat	Coverage 2 coats	Coverage 3 coats	Wood density	MEE_t for– t=1	t=7	t=14	t=21	t=28	t=35	t=60
		Ft²/gal			Lb/ft³	Pct						
				INTERIOR, UNPIGMENTED, NONAQUEOUS FINISHES								
17	1	—	—	—	22.6	-1	-1	-1	—	—	—	—
18	1	382	—	—	23.3	40	4	1	—	—	—	—
18	2	390	451	—	23.1	70	22	8	—	—	—	—
18	3	380	460	392	23.4	79	37	19	—	—	—	—
19	1	616	—	—	23.5	52	8	3	—	—	—	—
19	2	630	781	—	24.0	81	38	18	—	—	—	—
19	3	635	708	922	24.8	87	53	31	—	—	—	—
20	1	512	—	—	25.7	35	6	2	—	—	—	—
20	2	532	706	—	26.3	78	39	21	—	—	—	—
20	3	522	708	758	25.3	86	53	31	—	—	—	—
21	1	573	—	—	22.4	77	18	4	—	—	—	—
21	2	608	639	—	23.0	89	49	21	—	—	—	—
21	3	627	626	647	22.4	93	65	36	—	—	—	—
22	1	457	—	—	25.7	59	9	2	—	—	—	—
22	2	474	580	—	25.6	86	47	25	—	—	—	—
22	3	416	651	631	25.7	91	67	46	—	—	—	—
23	1	405	—	—	23.4	65	11	3	—	—	—	—
23	2	469	509	—	23.6	84	43	20	—	—	—	—
23	3	422	515	480	24.4	91	63	42	—	—	—	—
24	1	552	—	—	26.0	54	11	3	—	—	—	—
24	2	505	683	—	22.5	87	54	34	—	—	—	—
24	3	487	695	729	22.4	92	69	50	**37**	—	—	—
25	1	576	—	—	22.5	31	1	-1	—	—	—	—
25	2	564	713	—	22.5	80	37	18	—	—	—	—
25	3	569	774	821	23.2	88	56	35	—	—	—	—
26	1	550	—	—	25.6	53	9	1	—	—	—	—
26	2	554	640	—	25.8	87	53	28	—	—	—	—
26	3	535	699	760	25.6	91	66	44	—	—	—	—
27	1	585	—	—	25.8	48	7	1	—	—	—	—
27	2	594	724	—	26.2	79	35	14	—	—	—	—
27	3	598	671	587	26.6	88	55	32	—	—	—	—
28	1	596	—	—	22.2	71	22	8	—	—	—	—
28	2	644	752	—	22.1	86	52	29	—	—	—	—
28	3	664	824	819	22.5	90	64	43	—	—	—	—
29	1	—	—	—	26.9	-1	0	0	—	—	—	—
29	2	—	—	—	26.9	-1	1	1	—	—	—	—
29	3	—	—	—	26.5	2	1	0	—	—	—	—
30	1	330	—	—	21.8	97	83	69	60	52	46	27
31	1	416	—	—	23.1	-4	-6	-6	—	—	—	—
31	2	423	472	—	23.7	-1	-5	-5	—	—	—	—
31	3	477	466	673	24.4	2	-1	-2	—	—	—	—
32	1	—	—	—	22.3	6	-2	-2	—	—	—	—
32	2	—	—	—	23.5	11	-2	-3	—	—	—	—
32	3	—	—	—	23.9	17	-0	-1	—	—	—	—
33	1	503	—	—	24.4	24	3	1	—	—	—	—
33	2	507	688	—	24.0	77	33	13	—	—	—	—
33	3	483	734	802	24.3	85	52	31	—	—	—	—
34	1	644	—	—	27.3	66	20	8	—	—	—	—
34	2	597	831	—	26.4	85	49	27	—	—	—	—
34	3	632	846	734	25.9	90	63	41	—	—	—	—
35	1	360	—	—	24.4	58	15	7	—	—	—	—
35	2	336	422	—	25.2	80	45	24	—	—	—	—
35	3	379	405	378	25.2	88	61	40	—	—	—	—

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Table 1.—Moisture–excluding effectiveness (MEE_t) of finishes on ponderosa pine sapwood (after t days exposure at 90 pct relative humidity, average of three replicates)–con.

Finish[a]	Number of coats	Coverage			Wood density	MEE_t for–						
		1 coat	2 coats	3 coats		t=1	t=7	t=14	t=21	t=28	t=35	t=60
		-----------Ft^2/gal-----------			LB/ft^3	---------------------------Pct---------------------------						
				INTERIOR, UNPIGMENTED, AQUEOUS FINISHES								
36	1	485	—	—	23.3	44	-1	-1	—	—	—	—
36	2	503	607	—	23.5	62	6	6	—	—	—	—
36	3	509	660	750	24.4	68	24	10	—	—	—	—
37	1	500	—	—	23.1	38	2	-1	—	—	—	—
37	2	468	690	—	23.3	58	12	5	—	—	—	—
37	3	514	687	702	23.3	65	14	2	—	—	—	—
38	1	622	—	—	24.6	25	0	-1	—	—	—	—
38	2	624	862	—	27.4	61	11	3	—	—	—	—
38	3	570	783	795	24.1	70	22	11	—	—	—	—
39	1	463	—	—	22.2	-1	-1	-1	—	—	—	—
39	2	466	597	—	21.6	5	-3	-3	—	—	—	—
39	3	456	640	811	21.0	25	-2	-4	—	—	—	—
				EXTERIOR, PIGMENTED, NONAQUEOUS FINISHES								
40	1	545	—	—	23.4	88	55	32	—	—	—	—
40	2	492	545	—	23.6	97	87	76	68	60	54	37
40	3	505	504	618	24.1	98	91	84	78	72	67	53
41	1	498	—	—	23.3	91	64	43	—	—	—	—
41	2	519	621	—	24.0	96	85	72	63	55	48	—
41	3	499	652	594	23.6	98	90	81	74	68	62	45
42	1	529	—	—	23.5	90	60	39	—	—	—	—
42	2	534	598	—	23.6	97	85	74	63	55	47	—
42	3	515	571	554	24.0	98	91	84	77	71	65	49
43	1	523	—	—	23.5	92	61	41	—	—	—	—
43	2	514	591	—	24.2	97	87	77	68	60	53	36
43	3	476	577	713	24.3	98	91	84	78	72	66	51
44	1	494	—	—	25.1	91	66	44	—	—	—	—
44	2	480	755	—	25.3	94	79	62	53	—	—	—
44	3	459	686	827	25.3	96	86	74	67	58	49	—
45	1	691	—	—	26.8	22	1	-0	67	—	—	—
45	2	677	831	—	24.5	76	28	12	—	—	—	—
45	3	597	797	1047	24.9	89	57	32	—	—	—	—
46	1	665	—	—	27.6	61	16	6	—	—	—	—
46	2	670	791	—	26.8	85	51	30	—	—	—	—
46	3	658	677	815	26.7	90	66	46	—	—	—	—
47	1	682	—	—	26.9	79	38	18	—	—	—	—
47	2	662	699	—	27.0	91	66	46	—	—	—	—
47	3	625	791	849	27.3	93	74	57	44	—	—	—
48	1	544	—	—	24.9	77	37	18	—	—	—	—
48	2	496	807	—	25.1	89	62	41	—	—	—	—
48	3	516	630	842	25.2	92	71	53	45	—	—	—
49	1	444	—	—	24.6	66	21	10	—	—	—	—
50	1	616	—	—	26.3	62	14	3	—	—	—	—
50	2	678	1066	—	25.2	70	21	6	—	—	—	—
50	3	614	1085	1061	25.5	76	30	11	—	—	—	—
51	1	519	—	—	25.2	69	20	6	—	—	—	—
51	2	594	1132	—	25.3	87	55	32	—	—	—	—
51	3	597	1078	1090	25.8	91	69	49	—	—	—	—
52	1	649	—	—	25.5	37	2	-1	—	—	—	—
52	2	620	468	—	25.4	87	52	28	—	—	—	—
52	3	612	505	554	25.6	93	70	48	—	—	—	—
53	1	651	—	—	24.5	82	39	16	—	—	—	—
53	2	621	648	—	24.1	93	70	48	30	—	—	—
53	3	612	588	645	23.7	95	80	64	49	38	—	—

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Table 1.—Moisture–excluding effectiveness (MEE_t) of finishes on ponderosa pine sapwood (after t days exposure at 90 pct relative humidity, average of three replicates)-con.

Finish[a]	Number of coats	Coverage 1 coat	2 coats	3 coats	Wood density	MEE_t for– t=1	t=7	t=14	t=21	t=28	t=35	t=60
		----------- Ft^2/gal -----------			Lb/ft^3	---------------------- Pct ----------------------						
EXTERIOR, PIGMENTED, NONAQUEOUS FINISHES—con.												
54	1	576	—	—	25.7	75	30	12	—	—	—	—
54	2	561	639	—	26.0	88	59	36	—	—	—	—
54	3	536	599	647	26.0	91	69	48	35	—	—	—
55	1	622	—	—	25.5	7	–1	–1	—	—	—	—
55	2	662	961	—	24.7	13	–2	–3	—	—	—	—
55	3	670	991	987	24.8	21	1	–0	—	—	—	—
56	1	659	—	—	27.1	45	7	1	—	—	—	—
56	2	647	878	—	26.7	84	48	26	—	—	—	—
56	3	626	868	820	27.0	90	64	42	—	—	—	—
57	1	586	—	—	25.1	72	23	8	—	—	—	—
57	2	553	671	—	25.0	86	52	29	—	—	—	—
57	3	592	654	771	25.1	90	63	41	—	—	—	—
58	1	557	—	—	23.7	85	46	24	—	—	—	—
58	2	527	659	—	23.4	93	70	50	—	—	—	—
58	3	487	702	621	23.4	95	78	62	50	42	—	—
COMBINATION EXTERIOR/INTERIOR, PIGMENTED, NONAQUEOUS FINISHES												
59	1	439	—	—	23.4	82	37	18	—	—	—	—
59	2	397	480	—	22.9	93	69	49	36	—	—	—
59	3	444	474	443	22.6	94	76	59	47	—	—	—
60	1	—	—	—	23.9	91	67	44	—	—	—	—
60	2	—	—	—	24.0	95	81	65	54	45	—	—
60	3	—	—	—	24.0	96	85	73	64	56	50	—
61	1	542	—	—	21.1	83	27	7	—	—	—	—
61	2	538	705	—	21.2	94	63	32	—	—	—	—
61	3	492	708	728	21.2	96	75	52	30	—	—	—
62	1	521	—	—	24.4	80	31	15	—	—	—	—
62	2	534	766	—	23.7	89	53	35	—	—	—	—
62	3	562	699	888	23.4	92	63	45	—	—	—	—
63	1	436	—	—	25.3	93	77	53	38	—	—	—
63	2	429	532	—	26.2	98	90	82	74	67	60	40
63	3	426	467	498	25.6	98	93	87	82	76	71	57
64	1	353	—	—	25.8	94	77	59	44	—	—	—
64	2	342	353	—	26.0	97	91	83	76	69	62	42
64	3	333	351	387	26.2	98	94	88	83	78	74	58
65	1	490	—	—	21.5	88	48	25	—	—	—	—
65	2	493	877	—	21.8	94	73	54	40	—	—	—
65	3	477	914	945	21.9	96	80	65	52	42	—	—
66	1	428	—	—	22.0	89	56	33	—	—	—	—
66	2	412	835	—	22.1	95	77	61	47	—	—	—
66	3	434	757	980	22.5	96	83	70	58	48	—	—
67	1	429	—	—	23.6	93	69	50	38	—	—	—
67	2	413	672	—	24.0	96	83	70	60	50	42	—
67	3	397	608	534	24.2	97	89	80	72	65	58	41
68	1	466	—	—	24.1	78	35	16	—	—	—	—
68	2	456	610	—	24.5	**88**	58	37	—	—	—	—
68	3	458	639	728	24.7	91	66	47	—	—	—	—
69	1	435	—	—	21.7	93	64	39	—	—	—	—
69	2	411	383	—	21.6	98	88	78	69	60	52	30
69	3	400	377	554	21.2	98	90	83	75	68	62	43
70	1	371	—	—	23.7	86	45	23	—	—	—	—
70	2	357	469	—	23.8	91	65	43	—	—	—	—
70	3	399	495	502	24.5	93	72	52	40	—	—	—

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Table 1.—Moisture–excluding effectiveness (MEE_t) of finishes on ponderosa pine sapwood (after t days exposure at 90 pct relative humidity, average of three replicates)—con.

Finish[a]	Number of coats	Coverage 1 coat	Coverage 2 coats	Coverage 3 coats	Wood density	MEE_t for— t=1	t=7	t=14	t=21	t=28	t=35	t=60
		----------- Ft^2/gal	-----------		Lb/ft^3	-------------------			Pct	-------------------		
COMBINATION EXTERIOR/INTERIOR, PIGMENTED, NONAQUEOUS FINISHES—con.												
71	1	510	—	—	22.7	80	35	13	—	—	—	—
71	2	458	884	—	22.5	97	87	76	67	58	50	—
71	3	513	915	938	22.9	98	91	82	74	68	61	45
72	1	541	—	—	24.4	72	27	11	—	—	—	—
72	2	572	757	—	24.3	84	48	27	—	—	—	—
72	3	566	715	1082	24.2	58	58	37	—	—	—	—
73	1	330	—	—	25.9	91	62	41	—	—	—	—
73	2	343	396	—	25.1	94	77	61	49	—	—	—
73	3	370	358	378	25.2	96	82	70	59	51	—	—
74	1	460	—	—	22.9	79	35	16	—	—	—	—
74	2	461	659	—	23.3	89	61	38	—	—	—	—
74	3	454	666	589	23.2	92	70	50	36	—	—	—
75	1	388	—	—	23.6	88	51	28	—	—	—	—
75	2	385	475	—	23.7	94	75	56	42	—	—	—
75	3	382	449	510	22.6	96	82	67	55	46	—	—
INTERIOR, PIGMENTED, NONAQUEOUS FINISHES												
76	1	341	—	—	25.2	9	–1	–2	—	—	—	—
76	2	303	378	—	25.5	25	2	–1	—	—	—	—
76	3	290	383	375	25.8	37	5	–1	—	—	—	—
77	1	407	—	—	25.8	83	45	25	—	—	—	—
77	2	468	666	—	26.2	91	64	43	—	—	—	—
77	3	396	599	567	25.7	94	76	59	46	—	—	—
78	1	365	—	—	22.4	92	71	52	39	—	—	—
78	2	357	506	—	22.4	95	83	71	60	52	44	—
78	3	362	523	493	22.1	97	88	78	69	62	55	38
EXTERIOR, PIGMENTED, AQUEOUS FINISHES												
79	1	248	—	—	24.6	43	6	1	—	—	—	—
79	2	218	359	—	24.4	67	14	2	—	—	—	—
79	3	236	289	382	25.3	72	20	4	—	—	—	—
80	1	495	—	—	24.8	52	12	5	—	—	—	—
80	2	471	609	—	24.4	77	28	11	—	—	—	—
80	3	478	528	541	24.5	84	39	16	—	—	—	—
81	1	446	—	—	23.1	28	1	–1	—	—	—	—
81	2	445	697	—	22.9	50	6	2	—	—	—	—
81	3	421	660	663	23.4	59	10	5	—	—	—	—
82	1	428	—	—	23.3	43	2	–0	—	—	—	—
82	2	423	710	—	23.8	53	2	–3	—	—	—	—
82	3	454	654	686	22.8	60	8	2	—	—	—	—
83	1	455	—	—	26.5	5	–1	–1	—	—	—	—
83	2	460	544	—	26.0	38	4	–0	—	—	—	—
83	3	497	551	549	26.2	50	6	–0	—	—	—	—
84	1	415	—	—	23.4	30	3	0	—	—	—	—
84	2	459	599	—	23.3	48	11	5	—	—	—	—
84	3	456	615	686	22.6	45	11	5	—	—	—	—
COMBINATION EXTERIOR/INTERIOR, PIGMENTED, AQUEOUS FINISHES												
85	1	322	—	—	25.5	50	10	3	—	—	—	—
85	2	328	426	—	25.9	66	17	5	—	—	—	—
85	3	303	427	419	25.6	73	26	10	—	—	—	—
86	1	424	—	—	27.3	29	3	–1	—	—	—	—
86	2	415	602	—	27.1	38	8	2	—	—	—	—
86	3	374	635	599	27.3	44	8	1	—	—	—	—

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Table 1.—Moisture–excluding effectiveness (MEE_t) of finishes on ponderosa pine sapwood (after t days exposure at 90 pct relative humidity, average of three replicates)—con.

Finish[a]	Number of coats	Coverage			Wood density	MEE_t for—						
		1 coat	2 coats	3 coats		t=1	t=7	t=14	t=21	t=28	t=35	t=60
		Ft^2/gal			Lb/ft^3	Pct						
					INTERIOR, PIGMENTED, AQUEOUS FINISHES							
87	1	408	—	—	24.4	23	1	–0	—	—	—	—
87	2	422	620	—	24.3	45	5	–1	—	—	—	—
87	3	396	567	578	25.4	49	8	–0	—	—	—	—
88	1	465	—	—	24.8	40	6	2	—	—	—	—
88	2	442	532	—	25.1	51	9	2	—	—	—	—
88	3	439	541	570	25.6	58	11	2	—	—	—	—
89	1	406	—	—	25.7	36	3	–1	—	—	—	—
89	2	433	596	—	25.9	44	5	–0	—	—	—	—
89	3	413	533	611	26.1	48	11	3	—	—	—	—
90	1	314	—	—	22.7	78	37	20	—	—	—	—
90	2	312	439	—	21.0	86	47	27	—	—	—	—
90	3	304	441	413	21.5	88	55	33	—	—	—	—
91	1	355	—	—	24.5	5	–5	–5	—	—	—	—
91	2	315	440	—	24.2	11	–6	–6	—	—	—	—
91	3	364	423	464	23.8	22	–3	–3	—	—	—	—

[a]For complete data, see (*8*).

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Results and Discussion

The protection afforded by finishes excluding moisture from wood depends on a great number of variables (*4, 23, 25*). Among them are finish film thickness, type and amount of pigment, chemical composition and amount of the vehicle, volume ratio of pigment to vehicle, vapor-pressure gradient across the film, and length of exposure period. Under outdoor conditions, the age of the weathered finish is very important (*12, 23*). We investigated particularly the effects of varying film thickness (number of coats), length of exposure time, and chemical composition of the finish system. Additional studies included the effect of sample size, role of cycling humidity, effect of substrates (different woods and wood panel products), and brush versus dip application of the finish.

MEE of Wood Finishes

The data in table 1 show the wide range of MEE values found on ponderosa pine at 90 percent RH for the 91 finishes in the study. MEE always decreases with exposure time and always increases with greater film thickness (i.e. two coats of a finish are better than one, and three are better than two). The effects of finish type, number of coats, and exposure time on MEE are shown in figures 2 and 3 for several of the finishes evaluated (see also section on MEE and Film Thickness). The sheathing epoxy finish (finish 6, fig. 2) was very effective and had a relatively high MEE_{35} of 74 and 81 percent when the finish was applied in two or three coats. This is an unusual finish in that it is composed of virtually 100 percent solids (Appendix B) while the other finishes range from 20 to 80 percent solids.

In contrast to the epoxy sheathing compound (finish 6, fig. 2) a latex house paint (finish 80) and a nitrocellulose lacquer (finish 18, both in fig. 3) had low MEE values even with three coats. These permeable filmforming finishes do have a degree of protection against moisture vapor after 1 day at 90 percent RH, but the MEE falls very rapidly after that.

MEE and Finish Characteristics

As shown in Appendix A, this study included 16 aqueous (or water-borne) and 75 nonaqueous (solvent-borne) finishes; 52 were pigmented (opaque) and 39 were unpigmented (transparent). The finishes were also described as exterior grade, interior grade, or combination exterior/interior grade. These characteristics were important in determining the MEE of the finish when applied to wood surfaces.

The finishes were ranked from highest to lowest MEE for each day of measurement by the number of coats applied. For convenience, only the first 30 finishes in each ranking at each period of exposure are considered here. From table 2 it can be seen that the dominant characteristics of the 30 finishes with highest MEE are nonaqueous, pigmented, and either exterior grade or combination exterior/interior grade.

Table 2.—Distribution of finish characteristics for the 30 finishes with highest moisture-excluding effectiveness

Duration of test	Number of coats	Number of finishes: Combination exterior/interior	+	Exterior	+	Interior	Pigmented + unpigmented	Aqueous + nonaqueous
Days								
1	1	16	+	10	+	4	28 + 2	1 + 29
1	2	17	+	11	+	2	27 + 3	0 + 30
1	3	16	+	11	+	3	26 + 4	0 + 30
7	1	17	+	9	+	4	27 + 3	1 + 29
7	2	17	+	11	+	2	27 + 3	0 + 30
7	3	16	+	11	+	3	26 + 4	0 + 30
14	1	17	+	9	+	4	28 + 2	1 + 29
14	2	17	+	10	+	3	26 + 4	0 + 30
14	3	17	+	10	+	3	25 + 5	0 + 30

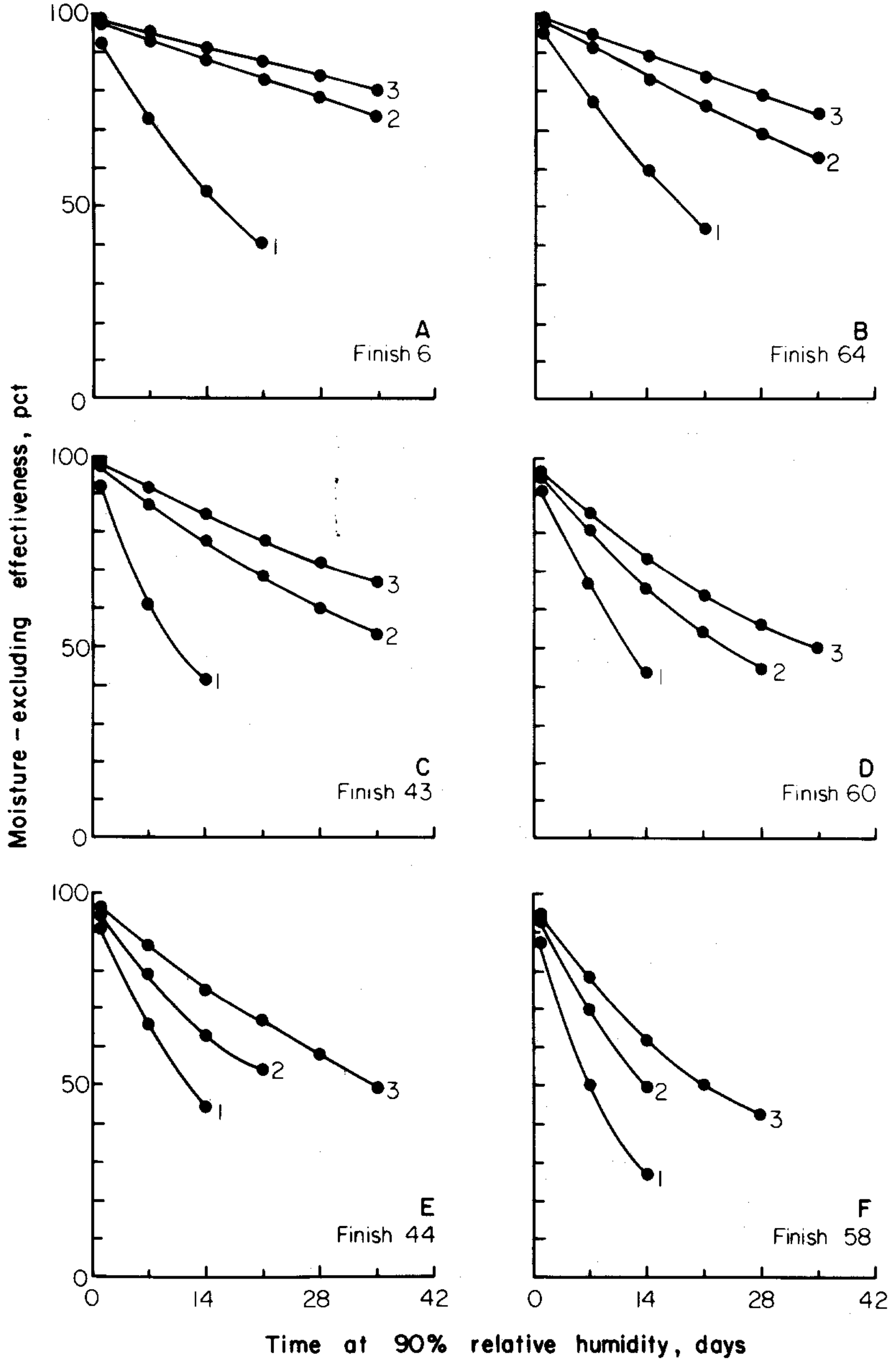

Figure 2.—Moisture-excluding effectiveness (MEE) of wood finishes on ponderosa pine sapwood at 90 percent relative humidity and 80 °F as a function of time. Number of coats is displayed at right of cuves. A. Finish 6: Two-component sheathing epoxy; B. Finish 64: Two-component epoxy/polyamide paint: C. Finish 43: Aluminum-pigmented varnish; D. Finish 60: Pigmented flat shellac; E. Finish 44: Two-component polyurethane gloss paint: F. Finish 58: Tall maleic alkyd/soya alkyd flat primer paint.

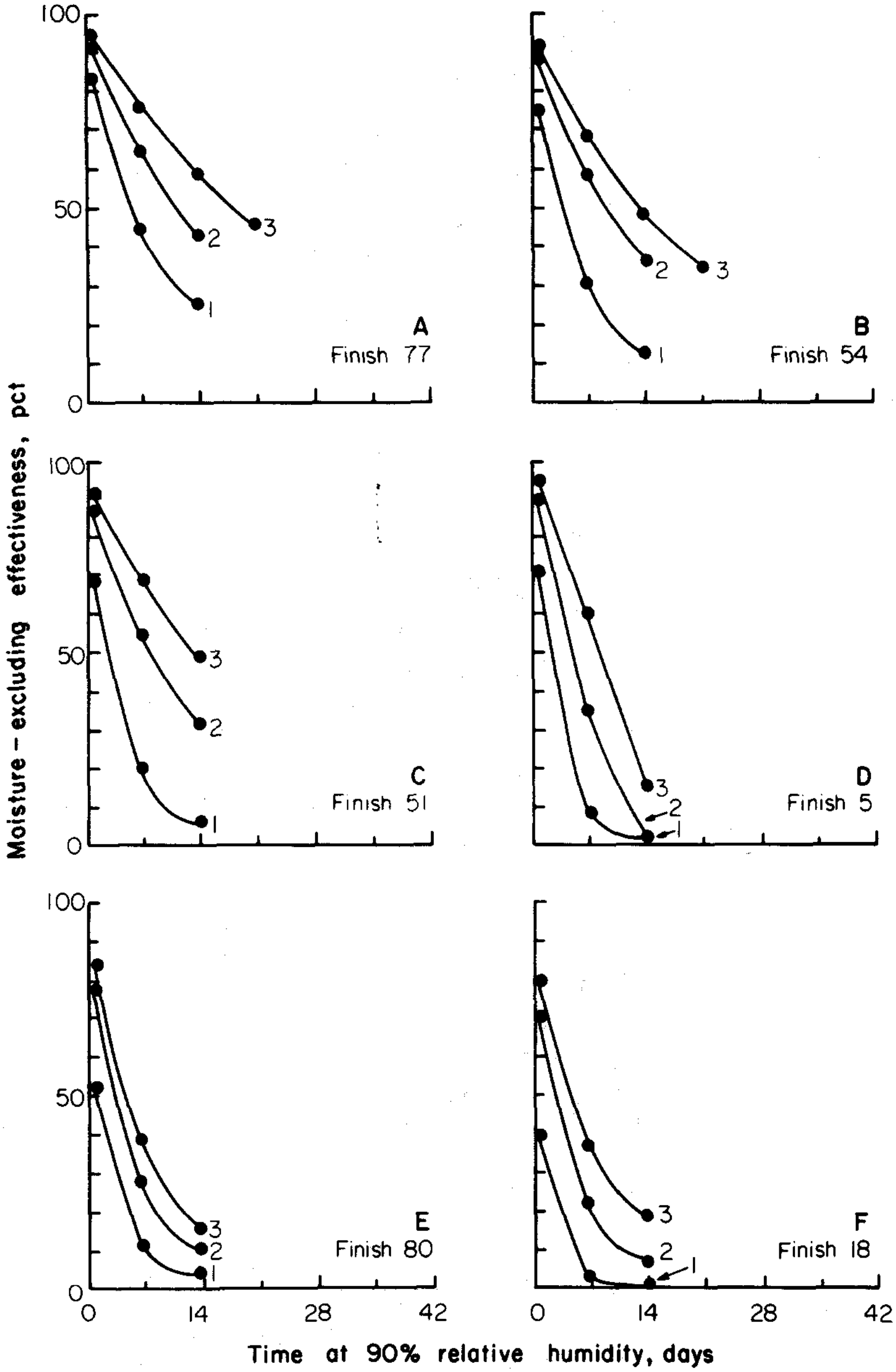

Figure 3.—Moisture-excluding effectiveness (MEE) of wood finishes on ponderosa pine sapwood at 90 percent relative humidity and 80 °F as a function of time. Number of coats is displayed at right of curves. A. Finish 77: Soya alkyd gloss enamel; B. Finish 54: Soya/silicone alkyd gloss enamel: C. Finish 51: Semitransparent linseed oil-based stain; D. Finish 5: Modified butyl-acrylo-styro epoxy finish; E. Finish 80: Acrylic latex flat house paint; F. Finish 18: Nitrocellulose semi-gloss lacquer.

In table 3 a ranking of finishes with $MEE_{14} \geq 70$ percent regardless of the number of coats of finish shows a predominance of pigmented, nonaqueous, exterior or combination exterior/interior finishes. The best finishes (finishes 30 and 6) were special systems in that they did not contain any solvent. Also, finish 30 (paraffin wax) was applied by dipping or brushing the melted material. This special finish is discussed in a separate section.

The individual conventional finishes with the best MEE_{14} were the two-component epoxies (finishes 63, 64 and 69), aluminum-pigmented varnishes (finishes 40-43), an aluminum paint (finish 71) and a soya-tung alkyd satin enamel paint (finish 67). The two-component epoxy/polyamide paints or enamels in gloss, or satin finish had a higher MEE_{14} than the two-component polyurethane (finish 73). Generally, two-component epoxies were far better than two-component polyurethanes whether pigmented or unpigmented (table 1).

Of the 91 finishes used in this study, 87 were applied and evaluated as 1, 2, or 3 coats. The overall effectiveness of the 87 finishes against water vapor is illustrated in table 4 where the MEE values have been separated into four ranges. After 1 day at 90 percent RH, 31 of the 87 finishes had an MEE of 75 to 100 percent: with three coats, 63 finishes had MEE_1 of 75 to 100 percent. After 14 days there were no finishes with an MEE of 75 to 100 percent when one brush coat was applied, 7 with two coats, and only 11 with three brush coats of the finish. Thus, only 11 out of 87 commercial finishes were found to retard moisture vapor movement into wood between 30 and 90 percent RH with any degree of success over the relatively short time of 14 days and only when two or three coats were applied.

On the low end of the MEE ranges, 69 finishes had an MEE_{14} of 0 to 24 percent when only one coat was applied (table 4). Twenty-eight finishes were in this MEE range even with three coats.

Table 3.—Ranking of finishes with moisture-excluding effectiveness $MEE_{14} \geq 70$ percent after 14 days exposure at so percent relative humidity. All finishes were nonaqueous.

Finish	Number of coats	Finish characteristics	MEE_{14}[a]	Standard error
			Pct	
30[b]	1	Combination exterior/interior, unpigmented	95	3.7
6	3	Combination exterior/interior, unpigmented	91	0.7
6	2	Combination exterior/interior, unpigmented	88	1.4
64	3	Combination exterior/interior, pigmented	88	0.6
63	3	Combination exterior/interior, pigmented	87	0.3
43	3	Exterior, pigmented	84	1.1
40	3	Exterior, pigmented	84	1.1
42	3	Exterior, pigmented	84	1.7
69	3	Combination exterior/interior, pigmented	83	2.0
63	2	Combination exterior/interior, pigmented	82	0.5
71	3	Combination exterior/interior, pigmented	82	2.6
41	3	Extetior, pigmented	81	1.0
67	3	Combination exterior/interior, pigmented	80	1.4
64	2	Combination exterior/interior, pigmented	79	1.5
78	3	Interior, pigmented	78	2.3
69	2	Combination exterior/interior, pigmented	78	2.7
43	2	Exterior, pigmented	77	0.8
71	2	Combination exterior/interior, pigmented	76	2.9
40	2	Exterior, pigmented	76	1.7
42	2	Exterior, pigmented	74	2.1
44	3	Exterior, pigmented	74	1.8
60	3	Combination exterior/interior, pigmented	73	2.0
41	2	Exterior, pigmented	72	3.8
78	2	Interior, pigmented	71	3.2
67	2	Combination exterior/interior, pigmented	70	1.7
66	3	Combination exterior/interior, pigmented	70	3.9
73	3	Combination exterior/interior, pigmented	70	1.1

[a]Mean of three observations.

[b]Melted paraffin wax, dip applied.

Table 4.—Finishes in four ranges of moisture–excluding effectiveness (MEE) as a function of coat number and time al 90 percent relative humidity and 80 °F

Duration of test	Number of coats	Number of finishes[a] in MEE ranges of—			
		75-100 pct	50-74 pct	25-49 pct	0-24 pct
1	1	31	21	21	14
	2	60	11	8	8
	3	63	11	7	6
7	1	2	14	16	55
	2	16	23	21	27
	3	24	36	5	22
14	1	0	5	13	69
	2	7	11	27	42
	3	11	18	30	28

[a]Data from table 1. Eighty-seven finishes were applied to ponderosa pine in 1, 2, and 3 coats.

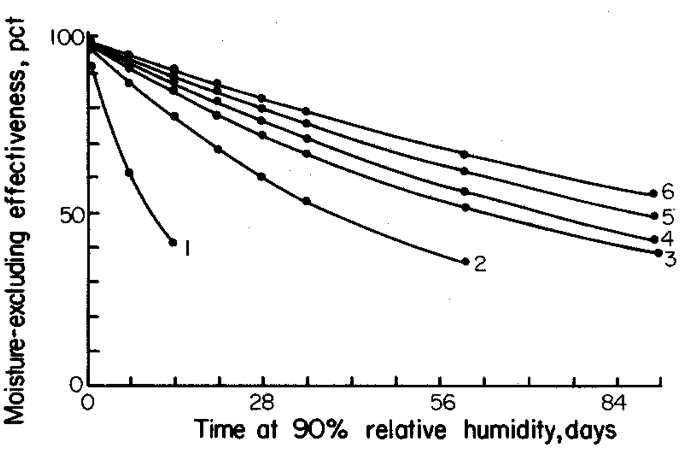

Figure 4.—Moisture-excluding effectiveness (MEE) of one to six coats of an aluminum flake-pigmented varnish (finish 43) on ponderosa pine sapwood at 90 percent relative humidity and 80 °F as a function of time. Number of coats is displayed to right of curves.

MEE and Film Thickness (Number of Coats of Finish)

The amount of finish applied to the wood surface is very important to MEE values, as shown in figures 2 and 3. Generally, the first and second coats are the most important in the overall MEE of the finish. The first coat serves to seal the wood but it is generally impossible to produce a totally defect-free uniform film over the wood. Also some penetration of resins or oils undoubtedly occurs (*3,5,10*). The second coat covers any defects of the first coat, and doubles the film thickness. Each succeeding coat increases MEE but, compared to the MEE produced by the first and second coats, later increments are relatively small and uniform even up to six coats (fig. 4). These small but uniform increases result from the fact that film thickness is doubled for the second coat but is increased only by one-third for the third, by one-fourth for the fourth and so on.

We investigated the effect of increasing film thickness (number of coats) up to six coats of finish for eight of the finishes described earlier (table 5). The results for aluminum flake-pigmented varnish (finish 43) illustrate the effect of six coats of a finish with an excellent MEE. At the opposite end, the acrylic latex house paint (finish 84) was quite porous to moisture vapor and had MEE_{14} of only 11 percent after six coats of finish were applied (table 5). The butadiene/styrene latex flat wall paint (finish 90) had an MEE_{14} of 20 percent for one coat and increased only to 45 percent for six coats. This paint is recommended by the manufacturer as a vapor barrier paint for interior walls (plaster, sheet rock, etc.).

The low values of MEE_{14} for latex finishes stand in contrast to those of the shellac-, varnish-, or paint-based finishes that we evaluated. A white shellac (alcohol solvent) (finish 23) with an MEE_{14} of 73 percent for six coats was less effective than a pigmented flat shellac (also alcohol solvent) (finish 60) which had MEE_{14} of 83 percent. For each coat applied the MEE increase was greater for the white shellac than for the pigmented shellac. This greater increase in MEE with each successive finish coat for a nonpigmented versus pigmented finish was also observed with the gloss urethane varnish (finish 13) and the aluminum flake-pigmented varnish (finish 43). Increases in MEE for the paints (finishes 67 and 77) were similar to those for the pigmented varnish and shellac. Browne (*4*) has done an extensive study on the variations of MEE for a linseed oil paint according to the nature of the pigment. In general, pigmented finishes have much higher MEE than unpigmented finishes for any specific resin system.

Table 5.—Coverage and moisture-excluding effectiveness (MEE_t) of six coats of finish on ponderosa pine sapwood (after t days exposure at 90 percent relative humidity, average of three replicates)

Finish	Number of coats	Wood density	Coverage						MEE_t							
			1 coat	2 coats	3 coats	4 coats	5 coats	6 coats	t=1	t=7	t=14	t=21	t=28	t=35	t=60	t=90
		Lb/ft^3	Ft^2/gal						Pct							
13	1	24.5	505	—	—	—	—	—	55	10	2	—	—	—	—	—
13	2	24.5	507	635	—	—	—	—	83	43	23	—	—	—	—	—
13	3	25.2	497	580	559	—	—	—	89	64	44	—	—	—	—	—
13	4	25.1	501	643	719	774	—	—	91	68	51	39	—	—	—	—
13	5	23.5	493	675	680	812	784	—	93	72	57	45	—	—	—	—
13	6	23.5	490	619	656	816	802	793	93	76	62	50	42	—	—	—
23	1	23.4	405	—	—	—	—	—	65	11	3	—	—	—	—	—
23	2	23.6	469	509	—	—	—	—	84	43	20	—	—	—	—	—
23	3	24.4	422	515	480	—	—	—	91	63	42	—	—	—	—	—
23	4	23.9	465	568	526	562	—	—	93	75	58	45	—	—	—	—
23	5	24.3	455	560	513	599	641	—	94	81	67	56	47	—	—	—
23	6	25.8	508	573	575	637	704	537	95	85	73	64	55	49	—	—
43	1	23.5	523	—	—	—	—	—	92	61	41	—	—	—	—	—
43	2	24.2	514	591	—	—	—	—	97	87	77	68	60	53	36	—
43	3	24.3	476	577	713	—	—	—	98	91	84	78	72	66	51	38
43	4	25.3	503	583	658	623	—	—	98	93	87	82	76	71	56	42
43	5	25.4	508	564	632	668	743	—	98	94	89	84	79	75	62	49
43	6	25.1	480	572	627	714	679	691	98	95	90	86	82	79	67	55
60	1	23.9	—	—	—	—	—	—	91	67	44	—	—	—	—	—
60	2	24.0	—	—	—	—	—	—	95	81	65	54	45	—	—	—
60	3	24.0	—	—	—	—	—	—	96	85	73	64	56	50	—	—
60	4	26.0	338	401	444	348	—	—	96	88	79	71	64	57	36	—
60	5	25.6	336	385	398	383	447	—	97	89	81	74	67	61	42	—
60	6	26.4	330	376	393	385	412	481	97	90	83	76	71	65	47	—
67	1	23.6	429	—	—	—	—	—	93	69	50	38	—	—	—	—
67	2	24.0	413	672	—	—	—	—	96	83	70	60	50	42	—	—
67	3	24.2	397	608	534	—	—	—	97	89	80	72	65	58	41	—
67	4	25.3	427	517	492	592	—	—	98	92	85	79	74	69	53	40
67	5	25.4	438	464	487	459	449	—	98	93	88	83	78	74	61	49
67	6	26.0	406	475	456	476	490	465	98	94	89	85	81	77	65	54
77	1	25.8	407	—	—	—	—	—	83	45	25	—	—	—	—	—
77	2	26.2	468	666	—	—	—	—	91	64	43	—	—	—	—	—
77	3	25.7	396	599	567	—	—	—	94	76	59	46	—	—	—	—
77	4	25.5	452	535	629	663	—	—	95	80	65	52	43	—	—	—
77	5	25.6	413	514	586	674	518	—	96	84	72	61	53	46	—	—
77	6	24.0	407	485	539	559	555	732	96	85	74	64	56	49	—	—
84	1	23.4	415	—	—	—	—	—	30	3	0	—	—	—	—	—
84	2	23.3	459	599	—	—	—	—	48	11	5	—	—	—	—	—
84	3	22.6	456	615	686	—	—	—	45	11	5	—	—	—	—	—
84	4	26.4	415	589	657	677	—	—	61	19	10	—	—	—	—	—
84	5	26.5	386	659	536	608	666	—	63	19	10	—	—	—	—	—
84	6	26.6	395	585	623	570	566	582	65	20	11	—	—	—	—	—
90	1	22.7	314	—	—	—	—	—	78	37	20	—	—	—	—	—
90	2	21.0	312	439	—	—	—	—	86	47	27	—	—	—	—	—
90	3	21.5	304	441	413	—	—	—	88	55	33	—	—	—	—	—
90	4	23.9	454	662	656	683	—	—	90	57	36	—	—	—	—	—
90	5	23.9	474	645	654	702	688	—	90	60	39	—	—	—	—	—
90	6	26.3	466	621	665	668	706	665	92	66	45	—	—	—	—	—

We investigated the dependence of MEE_{14} on the amount of material deposited on the surface of the specimen. Grouping finishes according to the three finish characteristics described earlier, we have six groups of nonaqueous finishes with average three-coat $MEE_{14} \geq 50$ percent:

	Characteristics	Number of finishes in the group
Unpigmented	Exterior	1
	Combination exterior/interior	2
	Interior	1
Pigmented	Exterior	8
	Combination exterior/interior	14
	Interior	2

To represent the amount of material deposited on the wood specimen, we calculated the total number of gallons applied per square foot and multiplied by the percent solids that each finish contained.

Scatter plots, for one, two, and three coats, showed that the relation between MEE_{14} and material deposited was strongest for one coat and comparable for two and three coats. The exterior grade pigmented finishes showed the most consistent positive relationship between MEE_{14} and material deposited, but clusters of finish types (finish 41, 43, 44 near one point, 47 and 48 near another) prevent a simple inference.

We calculated the correlation between MEE_{14} and the amount of material deposited for one, two, and three coats as follows, using data for all finishes that had three-coat $MEE_{14} \geq 50$ percent:

Number of coats	Correlation
1	0.592
2	0.402
3	0.405

MEE of Aluminum Flake-Pigmented Varnish

The effectiveness of aluminum flake pigments in varnish or paint systems has been recognized for a long time (*3,4,12,25,27*). We investigated the effect of adding several different aluminum flake pigments in paste form (2 lb/gal) to an exterior/interior grade polyurethane gloss varnish (finish 13, table 6). The MEE of the aluminum flake-pigmented varnishes (finishes 41-43) was highest for those prepared from flake pigments with the highest nonvolatile content and those with the highest leafing content (finishes 40 and 43, table 1). The role of film thickness in MEE was discussed earlier (fig. 4) for finish 43.

Table 6.—Aluminum leafing pigments used In preparing aluminum-pigmented varnishes

Finish[a]	Aluminum leafing pigment property			
	Retention on 325-mesh screen	Nonvolatiles	Leafing content	Bulking value
	------------------- *Pct*	-------------------		*Gal/lb*
40	0.35	73.1	70	0.084
41	0.5	65.0	60-65	0.082
42	0.2	65.0	65-70	0.084
43	4.0	67.0	70-80	0.081

[a]Pigment added to a gloss urethane varnish (finish 13) to give a final composition of 2 pounds aluminum paste per gallon of varnish. See Appendices A and B for description of finishes.

MEE of Combination Finishes

Paints and other finishes are often applied to wood surfaces as combinations of finishes, e.g. a sealer, primer, and a topcoat. Several different finish combination systems were evaluated for MEE (table 7). An all-acrylic latex house paint system (finishes 79 and 80) was found to have higher MEE_1 for the combination system than for the individual finishes and slightly higher MEE_7 but the MEE_{14} was virtually unchanged. The MEE_{14} for the combination primer/topcoat system (three coats) was essentially the same as the MEE_{14} for three coats of either finish (finishes 79 and 80, table 1). As noted earlier this observation is true of latex systems in general.

When the first coat (primer paint) was alkyd-based (finish 56) with a reasonably good MEE, the application of two coats of acrylic latex topcoat (finish 84) over the alkyd primer paint did not have any measurable effect on MEE. Thus, permeable latex paints have no effect on the MEE of less permeable alkyd finishes when the permeable paint is applied over the less permeable finish.

Table 7.—Moisture-excluding effectiveness (MEE_t) of combination wood finishes after t days exposure at 90 percent relative humidity (average of three replicates)

1st Coat		2nd Coat		3rd Coat		4th Coat		5th Coat		Mee_t for—		
Finish[a]	Coverage	Finish	Coverage	Finish	Coverage	Finish	Coverage	Finish	Coverage	t=1	t=7	t=14
	Ft²/gal		*Ft²/gal*		*Ft²/gal*		*Ft²/gal*		*Ft²/gal*	------- *Pct* -------		
79	248	—	—	—	—	—	—	—	—	44	4	–1
80	495	—	—	—	—	—	—	—	—	52	12	5
79	221	80	651	—	—	—	—	—	—	71	15	5
80	471	80	609	—	—	—	—	—	—	77	28	11
79	231	80	638	80	724	—	—	—	—	76	20	5
58	557	—	—	—	—	—	—	—	—	89	55	31
84	415	—	—	—	—	—	—	—	—	30	3	0
58	453	84	612	—	—	—	—	—	—	90	58	34
84	459	84	598	—	—	—	—	—	—	48	11	5
58	483	84	602	84	637	—	—	—	—	88	53	30
2	441	—	—	—	—	—	—	—	—	13	0	–2
49	444	—	—	—	—	—	—	—	—	66	21	10
2	441	49	538	—	—	—	—	—	—	86	51	35
46	669	46	791	—	—	—	—	—	—	85	51	30
2	434	49	490	46	968	46	603	—	—	97	90	82
47	662	47	699	—	—	—	—	—	—	91	66	46
2	454	49	486	47	851	47	716	—	—	98	92	87
48	496	48	807	—	—	—	—	—	—	89	62	41
2	467	49	535	48	721	48	685	—	—	97	91	85
25	564	25	713							80	37	18
32	—	—	—	—	—	—	—	—	—	6	–2	–2
25	589	25	783	32	—	—	—	—	—	89	57	34
16	545	16	593	—	—	—	—	—	—	84	46	27
29	—	29	—	—	—	—	—	—	—	1	1	1
16	689	16	976	29	—	29	—	—	—	81	41	19
35	379	35	405	35	378	—	—	—	—	88	61	40
35	360	35	394	35	491	29	—	29	—	86	54	31

[a]See Appendices A and B for description of finishes used.

Finishes 2 and 46-49 are recommended by the manufacturer for marine uses, particularly on boats. They are intended to be used as combination finish systems. The phenol-formaldehyde/linseed-tung wood sealer (finish 2) had a very low MEE for a one-coat flnish. The soya-linseed alkyd flat undercoat paint (finish 49) was only somewhat better (table 7). In combination, however, the MEE was better than the sum of the two finishes alone. When topcoat paints were applied over the sealer/primer combination (finishes 46-48) MEE was significantly increased and the four-coat system had MEE_{14}'s of 82, 87, and 85 percent, respectively. These topcoats were soya alkyd or alkyd marine enamels (Appendix A).

A paste wood wax (finish 32) does not provide protection against water vapor but does help improve the MEE of a two-coat phenolic/tung wood floor sealer (finish 25) (table 7). When two coats of a spray furniture polish (finish 29) were applied over either two coats of a polyurethane gloss varnish (finish 16) or three coats of a nitrocellulose/alkyd lacquer, the MEE_{14} was reduced slightly as were the other MEE values. The spray furniture polish by itself did not affect MEE at all even with two-coat application.

MEE of Paraffin Wax Treatments

Paraffin wax (finish 30) gave especially interesting results when the finish was melted and applied on the wood surface either by brushing or by dipping. Molten paraffin wax brush treatment gave the highest MEE_1 of all the 91 finishes investigated (table 1). MEE declined fairly quickly with time as was true for most one-coat finishes and MEE_{14} for one coat was 69 percent, still the highest MEE of all the one-coat finishes in the study. The results for a molten paraffin wax dip were even more impressive (fig. 5).

MEE_1 was 100 percent and MEE_{14}, 95 percent; MEE_{90} was still 70 percent. This method of applying paraffin wax gave the best results of any of the finishes investigated, regardless of the number of coats (tables 1 and 5). The presence of a near-perfect hydrophobic barrier on the wood surfaces produced very high MEE values (table 8).

Table 6.—Moisture-excluding effectiveness (MEE_t) of brush- and dip-applied finishes on ponderosa pine sapwood after t days exposure at 90 percent relative humidity (average of three replicates)

Finish	Application	Number of coats	Coverage 1 Coat	Coverage 2 Coats	Coverage 3 Coats	MEE_t for— t=1	t=7	t=14	t=21	t=28	t=35	t=60
			Ft^2/gal			Pct						
13	Brush	1	505	—	—	55	10	2	—	—	—	—
13	Brush	2	507	635	—	83	43	23	—	—	—	—
13	Brush	3	497	580	559	89	64	44	—	—	—	—
13	Dip	1	188	—	—	83	44	24	—	—	—	—
13	Dip	2	214	268	—	91	66	46	—	—	—	—
13	Dip	3	220	289	292	94	78	63	51	42	—	—
77	Brush	1	407	—	—	83	45	25	—	—	—	—
77	Brush	2	468	666	—	91	64	43	—	—	—	—
77	Brush	3	396	599	567	94	76	59	46	—	—	—
77	Dip	1	199	—	—	93	76	59	46	—	—	—
30	Brush	1	330	—	—	97	83	69	60	52	46	27
30	Dip	1	448	—	—	100	97	95	92	90	87	79

MEE for Brush Versus Dip Applications

The results for dipping versus brushing of molten paraffin wax prompted additional studies on how the two application methods affect MEE. The study was brief (table 8) and included one-, two-, and three-dip coats of an exterior grade polyurethane gloss varnish (finish 13) and a one-dip coat of a soya alkyd gloss enamel (finish 77). Results are also shown for the paraffin wax (finish 30), brushed and dipped.

We found that one-dip coat was equal to two-brush coats of the gloss varnish, but one-dip coat of the paint was equal to three-brush coats. MEE_{14} for the one-dip coat of paint was identical to that of three-brush coats on the ponderosa pine sapwood specimens. This beneficial effect of dipping is no doubt due to the fact that more finish material is applied to the wood surface (see coverage values in table 8), and because dipping for 30 seconds in the finish (whether paint, varnish, or molten paraffin wax) increases penetration and provides greater sealing of the end-grain of the wood.

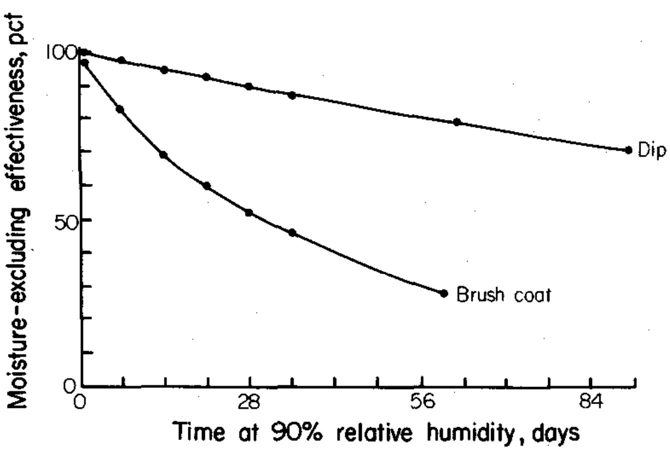

Figure 5.—Moisture-excluding effectiveness of one coat of paraffin wax (finish 30) applied by dipping or brushing of molten material on ponderosa pine sapwood at 90 percent relative humidity and 80 °F as a function of time. Method is displayed to right of curves.

MEE of Wood Finishes as a Function of Repeated Adsorption/Desorption Cycles

All of the discussion so far has dealt with the moisture-excluding effectiveness of relatively new or fresh finishes on wood surfaces. Normally, only 3 to 6 weeks time elapsed between applying the finish, equilibrating the finished specimens to 30 percent RH and then starting the MEE evaluation at 90 percent RH. The question arises, what happens with longer times? Does MEE change with time? What happens to MEE when the finished specimen goes through repeated cycles between 30 and 90 percent RH?

The effects of outdoor weathering on MEE have been addressed by earlier workers (*3,4,12,19,23*). We wanted to look at the effects of adsorption/desorption cycles between 30 and 90 percent RH and the accompanying effects of time in the test for MEE.

MEE and Noncontinuous Adsorption/Desorption Cycles

Generally, from 4 to 8 weeks elapsed between the time a new finish was applied to the wood surface and the time the MEE test was started at 90 percent RH. This was the time frame required for the sample to reach equilibrium moisture content (EMC) at 30 percent RH. This means that the finish was curing and drying for this duration before the test was begun. The MEE was then determined and the specimens stayed in test at 90 percent RH until MEE values fell below 50 percent (table 1). The specimens were then returned to 30 percent RH.

We selected 13 representative finishes with varying degrees of MEE to study the effects of repeat adsorption/desorption cycles on MEE (table 9). The first adsorption cycle varied from 2 to 17 weeks at 90 percent RH followed by a desorption cycle of 8 to 20 weeks at 30 percent RH to EMC. The second and third adsorption cycles were stopped after 14 days in test at 90 percent RH and the samples returned to 30 percent RH for equilibration. The specimens were brought to EMC at 30 percent RH between the second and third adsorption cycles just as before the first cycle. Thus, the minimum time that elapsed between the start of the first and third adsorption cycles was 18 weeks; maximum elapsed time was 59 weeks. The finished specimens with the highest MEE took longer to come to EMC between cycles than did the finished samples with lower MEE.

Table 9.—Repeated adsorption cycles: effect on the moisture-excluding effectiveness (MEE_t) of finishes on ponderosa pine sapwood (after t days exposure at 90 percent relative humidity, average of three replicates)

Finish	Number of coats	MEE_t for—								
		Cycle 1			Cycle 2			Cycle 3		
		t=1	t=7	t=14	t=1	t=7	t=14	t=1	t=7	t=14
		Pct								
13	1	55	10	2	57	13	5	57	14	5
13	2	83	43	23	85	49	29	84	51	32
13	3	89	64	44	91	68	50	90	69	52
13	4	91	68	51	91	69	51	92	70	52
13	5	93	72	57	92	73	57	93	74	58
13	6	93	76	62	93	77	61	94	77	62
23	1	65	11	3	48	9	3	46	8	3
23	2	84	43	20	85	48	27	86	48	28
23	3	91	63	42	93	72	55	94	74	57
23	4	93	75	58	94	80	65	96	82	69
23	5	94	81	67	96	85	73	97	87	76
23	6	95	85	73	97	88	79	97	90	81
30	1	97	83	69	94	77	62	94	74	59
43	1	92	61	41	91	66	49	90	65	48
43	2	97	87	77	97	89	82	98	90	83
43	3	98	91	84	98	93	88	98	93	89
52	1	37	2	–1	40	6	2	39	5	1
52	2	87	52	28	89	56	30	90	57	31
52	3	93	70	48	92	71	47	93	71	47
53	1	82	39	16	84	43	19	85	44	21
53	2	93	70	48	94	73	51	94	74	54
53	3	95	80	64	96	83	67	96	83	69
54	1	75	30	12	76	32	16	75	32	16
54	2	88	59	36	89	61	41	88	61	41
54	3	91	69	48	93	72	51	92	71	53
57	1	72	23	8	76	28	12	76	29	12
57	2	86	52	29	87	55	34	88	56	34
57	3	90	63	41	91	64	45	90	65	45
59	1	82	37	18	82	42	19	75	23	6
59	2	93	69	49	96	82	67	97	84	71
59	3	94	76	59	97	85	74	98	88	78
65	1	88	48	25	87	49	28	88	49	27
65	2	94	73	54	94	73	54	95	74	54
65	3	96	80	65	96	81	66	96	81	67
67	1	93	69	50	93	74	56	94	76	59
67	2	96	83	70	97	86	76	97	84	77
67	3	97	89	80	98	92	85	98	92	87
77	1	83	45	25	85	51	31	85	53	33
77	2	91	64	43	91	69	50	91	71	53
77	3	94	76	59	94	80	64	95	81	68
77	4	95	80	65	95	83	71	95	83	71
77	5	96	84	72	96	87	77	96	87	77
77	6	96	85	74	97	88	80	96	88	80
90	1	78	37	20	89	52	31	90	55	32
90	2	86	47	27	96	76	56	96	77	59
90	3	88	55	33	96	78	60	95	78	60

MEE was found to increase through each new adsorption/desorption cycle for nearly all the 13 finishes examined (table 9). Even one-coat finishes generally showed an increase in MEE in going from one cycle to the next. The largest increases in MEE were usually observed between the first and second cycles. This increase in MEE with time and repeat adsorption/desorption cycles is most likely caused by the continued curing of the finish and loss of any last small amounts of solvent that could be trapped in the finish film. The stresses placed on the film by the swelling and shrinking of the wood during adsorption and desorption were not sufficient to create any micro-crazing of the finish. This means permeability is not affected even for a relatively brittle finish like shellac (finish 23) and alkyd paints (finish 52) and MEE is not reduced. Even relatively thick films caused by applying six coats of finish (finishes 13, 23, and 77) were found to have slowly increasing MEE with each adsorption/desorption cycle.

Two of the finishes (a one-component epoxy enamel, finish 59, and a butadiene/styrene latex primer paint, finish 90) were found to have significantly higher MEE on the second adsorption cycle (figs. 6 and 7). These two finishes apparently undergo quite slow final cure of the resin in the finish, and the permeability of the finish film decreases with time and thus MEE increases. The increase in MEE was much smaller between cycles two and three, as it was with all the other finishes examined. These results show #at several weeks to several months may be required before any finish reaches its maximum MEE.

MEE and Continuous Adsorption/Desorption Cycles

In monitoring noncontinuous cycles we observed that moisture vapor movement through the finish when the humidity was increasing from 30 to 90 percent RH (adsorption) was greater than when decreasing from 90 to 30 percent (desorption) (fig. 8). For example, 100 days were required for a finished specimen to adsorb approximately 9 g H_2O/100 g ovendried (OD) wood at 90 percent RH but even after 170 days at 30 percent RH, only 7 g H_2O/100 g OD wood had been desorbed. Such behavior would be expected from the sorption hysteresis observed for wood and other cellulosic materials (*22*). Additionally, the vapor diffusion resistance of both wood and finish depends on the moisture content (MC) and the moisture gradient. These change with the different cycles studied.

Since water vapor movement through a finish is slower during desorption than during adsorption (fig. 8), a continuous regular cycling of the RH (such as would be found between summer and winter seasons, for example) could cause an overall increase in the wood moisture content if the adsorption/desorption periods were similar. Three of the finishes used in the noncontinuous adsorption/desorption studies were selected to demonstrate the effect of continuous humidity cycles on wood MC. New wood specimens were coated with one, two, or three coats of a

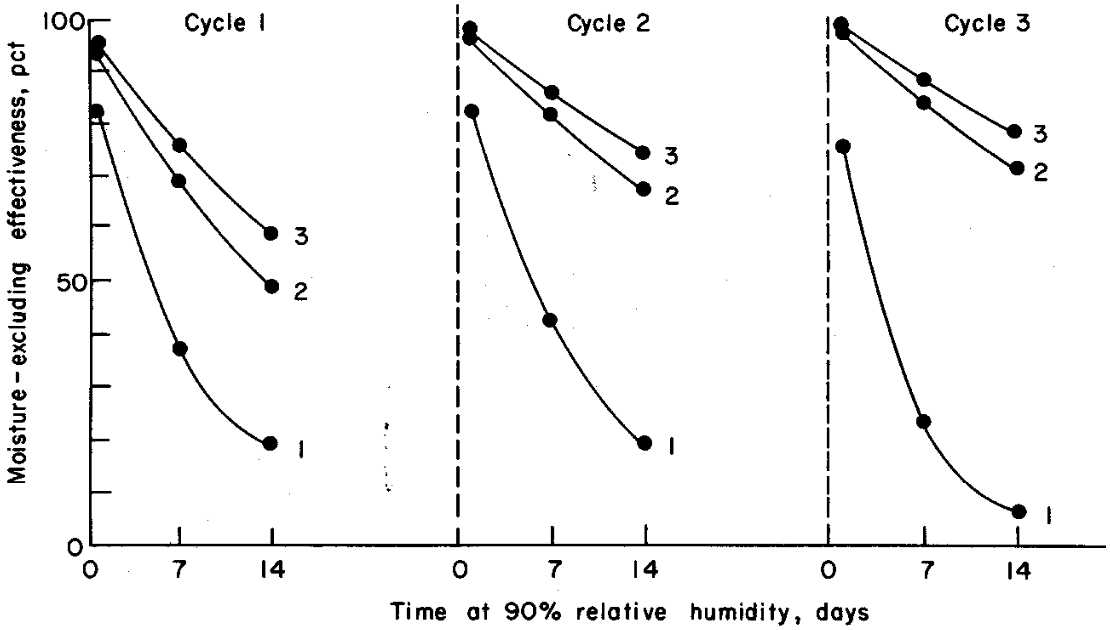

Figure 6.—Moisture-excluding effectiveness (MEE) of a one-component n epoxy enamel (finish 59) on ponderosa pine sapwood at 90 percent relative humidity (RH) and 80 °F as a function of time and for repeat adsorption cycles with equilibration to 30 percent RH and 80 °F between each cycle. Number of coats is displayed to right of curves.

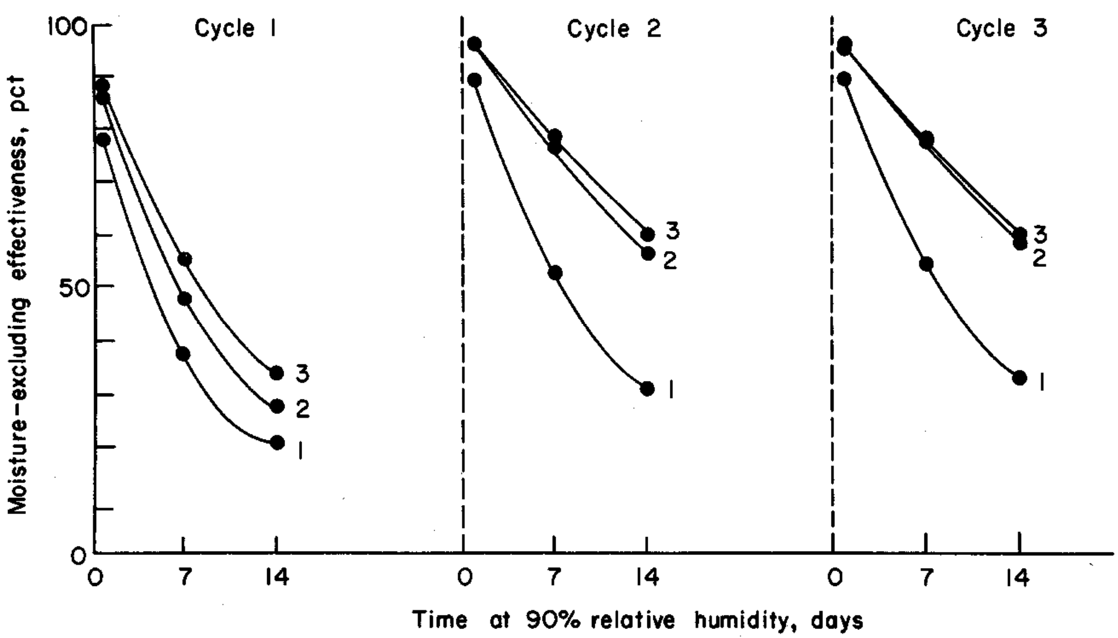

Figure 7.—Moisture-excluding effectiveness (MEE) of a butadiene/styrene latex primer paint (finish 90) on ponderosa pine sapwood at 90 percent relative humidity (RH) and 80 °F as a function of time and for repeat adsorption cycles with equilibration to 30 percent RH and 80 °F between each cycle. Number of coats is displayed to right of curves.

white shellac (finish 23), an aluminum-pigmented metal and masonry paint (finish 65), or a soya alkyd gloss enamel paint (finish 77). The coated wood specimens and their uncoated controls were conditioned to 30 percent RH for 30 days and then exposed to alternating cycles of 14 days at 90 percent and 14 days at 30 percent RH for three complete cycles (28 days per cycle, 84 days total).

The MC changes found for wood finished with the aluminum paint have been chosen to illustrate the results of the test (fig. 9). The uncoated wood was very near equilibrium after 14 days at either 30 or 90 percent RH and the second and third adsorption/desorption cycles caused only slightly more moisture in the specimens than the first. With one coat of finish however, the MC at the end of each 14-day period at either 30 or 90 percent RH was higher than that found for the previous cycle at the same RH. The effect was similar with three coats of finish except that the amount of moisture in the specimen was less because the finish had a higher MEE. These results show that the MC of a piece of wood finished with a high MEE finish slowly increases as RH increases and decreases over time periods that are not long enough for the piece to come to EMC. The times to reach EMC are very long for finishes with high MEE (figs. 7-9).

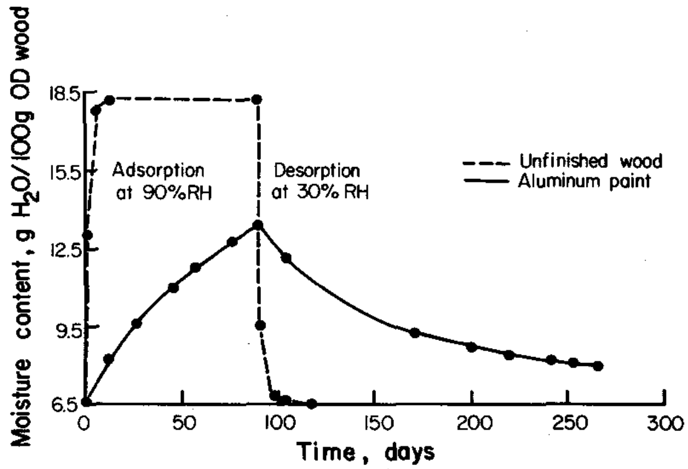

Figure 8.—Change in moisture content of ponderosa pine sapwood finished with three coats of aluminum paint (finish 65) when exposed to 90 percent and 30 percent relative humidity at 80 °F compared to unfinished wood.

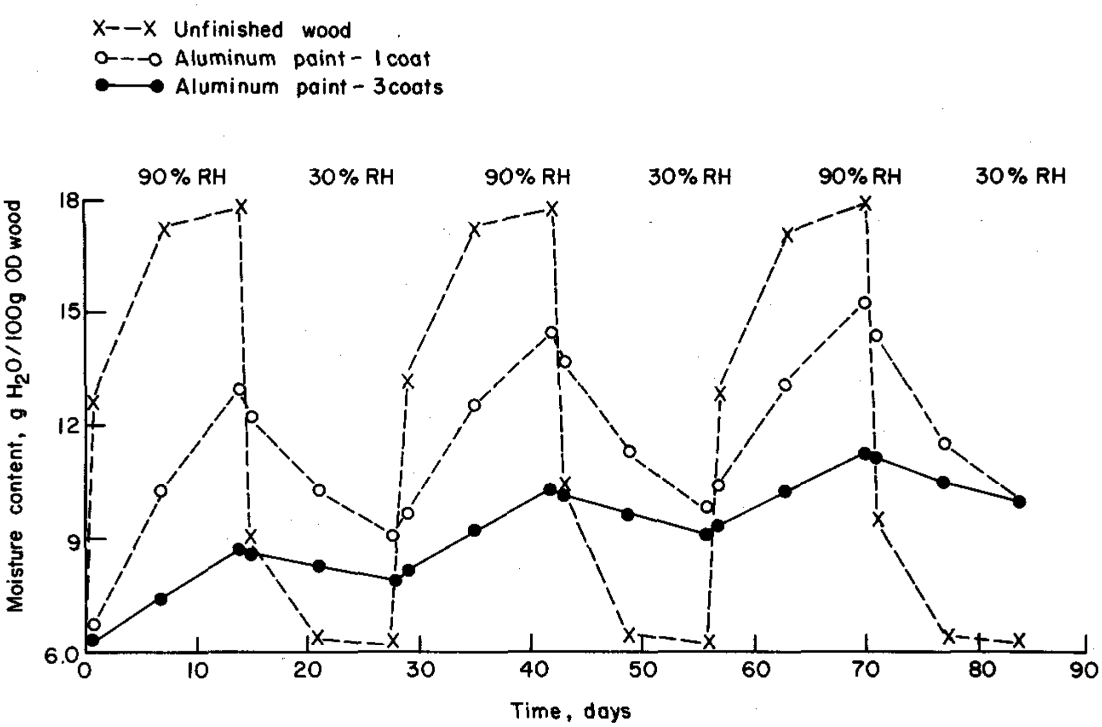

Figure 9.—Change in moisture content of ponderosa pine sapwood finished with one and three coats of aluminum paint (finish 65) when exposed to alternating cycles of 30 percent and 90 percent relative humidity at 80 °F.

MEE and the Role of the Substrate

Different Wood Species and Composite Wood Specimens

All of the results reported thus far have been for finishes on ponderosa pine sapwood. The MEE of any finish depends, in part, on the type of substrate to which the finish is applied. We investigated nine solid or composite wood substrates to determine the contribution of the substrate to MEE. A polyurethane gloss varnish (finish 13), soya-tung alkyd enamel (finish 67) and molten paraffin wax (finish 30, dip application) were chosen as finishes for this study. For convenience, only the MEE_{14} results are discussed (table 10).

The substrate and the related amount of finish (coverage) applied to the substrate have a significant effect on MEE for a given finish. This is best illustrated by comparing the results for western redcedar and hard maple. The varnish was applied in nearly equal amounts to these two solid wood substrates but the MEE on hard maple was greater than that on western redcedar by a factor of 10 for one-coat application. This large dfference decreased as more coats were applied but three-coat MEE_{14} on western redcedar was 48 percent compared to 78 percent on hard maple. This low MEE on western redcedar is probably related to the high oil content of this species compared to the other species investigated. Similar results were found for the enamel but the differences in MEE were not as large.

Table 10.—Moisture-excluding effectiveness (MEE_{14}) of three finishes on different substrates after 14 days at 90 percent relative humidity[a]

Wood substrate	Coverage						MEE_{14}		
	1 coat	2 coats		3 coats			1 coat	2 coats	3 coats
		1st	2nd	1st	2nd	3rd			
	Ft^2/gal						Pct		
				FINISH 13					
Ponderosa pine	484	458	510	473	563	534	9	41	55
Southern pine	574	543	726	577	724	888	29	65	77
Red oak	387	369	397	363	419	377	38	64	72
Douglas-fir plywood	412	374	498	378	504	464	29	60	74
Flakeboard	450	456	671	481	611	880	15	43	60
Western redcedar	358	339	390	313	356	435	5	28	48
Hard maple	361	357	381	422	376	427	57	73	78
Particleboard	307	317	469	294	459	419	22	40	62
Hardboard	314	324	424	307	450	438	36	55	64
				FINISH 67					
Ponderosa pine	411	382	463	366	379	444	56	77	85
Southern pine	560	512	845	497	853	776	62	81	87
Red oak	498	513	711	483	760	830	52	70	76
Douglas-fir plywood	342	344	525	348	525	471	74	83	88
Flakeboard	486	498	787	449	712	819	65	76	82
Western redcedar	564	507	851	547	787	917	37	58	66
Hard maple	585	548	797	513	815	747	63	78	84
Particleboard	328	316	468	319	474	431	67	79	85
Hardboard	391	347	523	360	513	498	64	76	81

[a]All values are averages of three replicates. For complete details see (8).

Red oak is a ring porous hardwood (25) and it was expected that the large vessels would be difficult to seal. Thus, one-coat MEE_{14} on red oak for the varnish was 38 percent compared to 57 percent on the diffuse porous hard maple at nearly equal coverages but three-coat MEE_{14} was nearly the same for both species (table 10). Even though more enamel was applied to the red oak than to the hard maple (i.e. coverage was lower for red oak), all MEE values (one, two, or three coats) for red oak were lower than that for hard maple.

The MEE of the varnish (finish 13) on the four composite wood products (Douglas-fir plywood; Douglas-fir flakeboard (*13*); particleboard; and hardboard) was influenced by the surface texture of the substrate especially for one and two coats of finish. The smooth-surface hardboard and Douglas-fir plywood had the highest one-coat MEE and the rough-surface flakeboard and particleboard, the lowest. Differences in MEE were less for two and especially for three coats. Similar trends were found for the enamel (finish 67) but the differences for this pigmented finish were much less than for the unpigmented varnish.

The MEE_{14} of one coat of paraffin wax (finish 30) applied by dipping, was affected by the general structure of the specimen. The results were as follows:

Ponderosa pine	62
Southern pine	90
Red oak	82
Douglas-fir plywood	42
Flakeboard	65
Western redcedar	89
Hard maple	99
Particleboard	53
Hardboard	89

Composite wood products that had surface and/or edge irregularities (Douglas-fir plywood, flakeboard, particleboard) had the lowest MEE; smooth specimens the highest (hardboard, southern pine, hard maple, western redcedar). The MEE of red oak was lower than that for hard maple, reflecting the difficulty of sealing the large red oak vessels. The western redcedar could be effectively sealed with paraffin wax and the oils and other extractives in western redcedar apparently did not disrupt the ability of the wax to prevent the penetration and adsorption of water into the wood. The MEE value for ponderosa pine was unexpectedly low (62 pct) as compared to the value of 95 percent found earlier for different samples (table 6).

Different Size Specimens

The size (3 x 5 x 5/8 in.) and shape of the specimens used in these studies were chosen to represent a typical predominantly flat-grained surface and for convenience. Since water is adsorbed more rapidly through the end grain of the wood (*22,25*) the size and shape of the wood specimen are expected to have an effect on MEE, as is the amount or ratio of end grain to lateral surface (tangential and radial). Ease of application and the size and shape of edges must also be important factors in determining the MEE of any finish.

We did only one brief study on shape and size of specimens. The soya-tung alkyd enamel (finish 87) was applied in one, two, or three brush coats to ponderosa pine, southern pine, red oak, Douglas-fir plywood, and Douglas-fir flakeboard wood specimens. Specimen sizes were 3 x 5 x 5/8 in. and 6 x 10 x 5/8 in. (tangential x longitudinal x radial). This means the flat grain (tangential) surface was increased by a factor of four while the end grain and vertical grain (radial) surfaces were increased by a factor of two in going from the small to the large specimens.

The results of this study (table 11) show that the MEE is affected most by the amount of finish (coverage) applied to the wood surface. The greater the amount applied (the lower the coverage in ft^2/gal), the greater the MEE. We found we could not consistently apply equal amounts of finish to the surfaces by brushing. In one case (ponderosa pine) the finish was applied at lower coverage for the small (3 x 5 in.) versus the large (6 x 10 in.) specimens. For three others (southern pine, red oak, flakeboard) the opposite was true. Only in the Douglas-fir plywood specimens were relatively equal quantities of finish applied to the surfaces. In this case the MEE_{14} found for the finish was only slightly higher for the large specimens than for the small specimens (for convenience only MEE_{14} values are shown in table 11, other MEE values were similar).

The overriding effects on MEE of coverage or amount of material applied to the wood surface are illustrated in figure 10. The MEE for each substrate for one, two, or three coats of finish is plotted against the total coverage of the finish. Each set (one, two, or three coats) shows a fairly close relationship between MEE and total or cumulative coverage (individual coverage values were added together for two- and three-coat applications). Assuming a linear relationship between MEE and coverage, regression analysis gave squared correlation coefficient (R^2) values for one, two, and three coats of 61, 48, and 47 percent, respectively.

Table 11.—Effect of specimen size and finish coverage on the moisture-excluding effectiveness (MEE_{14}) of finish 67 on different wood substrates after 14 days exposure at 90 percent relative humidity

Wood subtrate	Specimen Size	Coverage						MEE_{14}		
		1 coat	2 coats		3 coats			1 coat	2 coats	3 coats
			1st	2nd	1st	2nd	3rd			
	In.	Ft²/gal						Pct		
Ponderosa pine	3 x 5	429	413	672	397	608	534	56	77	85
	6 x 10	575	586	667	575	628	759	43	67	77
Southern pine	3 x 5	560	512	845	497	853	776	62	81	87
	6 x 10	419	417	495	390	472	493	73	85	90
Red oak	3 x 5	498	513	711	483	760	830	52	70	76
	6 x 10	415	403	437	422	436	453	60	80	86
Douglas-fir plywood	3 x 5	342	344	525	348	525	471	74	83	88
	6 x 10	331	345	424	325	443	510	77	87	90
Flakeboard	3 x 5	486	498	787	449	712	819	65	76	82
	6 x 10	297	316	396	327	386	437	72	83	86

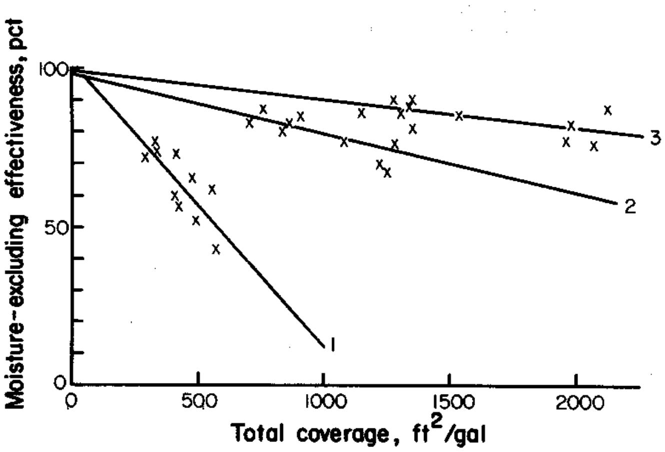

Figure 10.—Linear regression lines for moisture-excluding effectiveness (MEE) of 1, 2, and 3 coats of a soya-tong alkyd enamel (finish 67) as a function of coverage. For each coat number, each point derives from a different substrate.

Effect of Density of the Wood Specimen

In general, all other factors being constant, the higher the density of a wood specimen, the higher will be the nominal MEE of the finish applied to it. This dependence is roughly linear but changes with time from treatment–the slope gets steeper with the lapse of time. The dependence of MEE on density also weakens as the number of coats increases.

We investigated the relationship between wood density and MEE with scatter plots. Using a simple statistical model, we made an adjustment for the density of the wood specimens. Details of this adjustment are given in Appendix C. However, when we ranked the MEE values adjusted for the density of the wood specimens used in this study, we found only minor differences from the ranking of unadjusted values. For example, ranked by either type of MEE, the same finishes fell in categories excellent (>75 pct MEE) and good (50 to 75 pct MEE). There was one switch from fair (25 to 50 pct MEE) using unadjusted MEE's to poor (<25 pct MEE) using adjusted MEE's. To reduce the effect of density our experimental procedure called for three wood specimens as replicates, one each of low, medium, and high density, for each finish coat combination. This procedure seems to have been adequate.

Variability of MEE

The variation in MEE comes from several sources. Variation in density and variation in finishing are two major sources easy to identify. The contribution of density varies from finish to finish and, within finish, from one coat to two coats to three coats.

The finishes that show relatively little variance may be particularly impermeable to water. This seems likely for three coats of finishes 6, 63, and 64; for these, wood density should have little effect on MEE (see the right-hand column of table 3) The other identifiable component of MEE variability, coverage (equivalently, volume of finish applied), can decrease MEE variability as well as increase it. From plots and summary statistics, it seems that the small variation in coverage seen in this study usually has a small impact on MEE when only one substrate is considered. (In a few cases, notably finish 41, the relatively large amount of finish applied to the least dense specimens for one coat and three coats may reduce the variability that one might expect from considering only the effects of density.)

The MEE of modern surface finishes (paints, lacquers, varnishes, etc.) and intrasurface coatings (water repellents and wood sealers) was evaluated on clear ponderosa pine (*Pinus ponderosa*) sapwood. This substrate was used to determine the rate of vapor transmittance for all the finishes and combination of finishes used in these studies, and was the reference medium for extensions to other substrates. A diversified selection of commercially available finishes was evaluated.

Specimens

The degree of protection obtained from a finish as a vapor retarder is governed by the size and species of the specimen (*3,4,12*). The effects on MEE of nine wood substrates and two sample sizes were evaluated. All solid wood specimens were cut from flat-grained lumber of differing densities. A representative pair from each of three density ranges (high, medium, and low) was used to evaluate each coating.

Standard Specimens

Ponderosa pine sapwood was chosen as a representative, commercially available softwood substrate. The 3-inch (tangential) by 5-inch (longitudinal) by 5/8-inch (radial) clear specimens had the corners, ends and edges rounded to a 1/4-inch radius by routing and then sanding. This shape decreased application difficulties and damage due to handling of the finished surfaces (fig. 1).

Specimens from Other Substrates

Nine wood substrates were used to evaluate differences between species of a few selected finishes. The specimens were cut from the following substrates. (Note exceptions to the standard ponderosa pine dimensions for some of the wood composite products):

1. Douglas-fir plywood.–Commercial, exterior-grade Douglas-fir (*Pseudotsuga menziesii*) heartwood plywood (3 x 5 x 5/8 in.).

2. Hardboard.–Commercial, sanded, exterior-grade hardboard (3 x 5 x 3/8 in.).

3. Particleboard.–Commercial, exterior-grade, softwood, particleboard (3 x 5 x 5/8 in.).

4. Flakeboard.–Structural flakeboard manufactured from Douglas-fir at the Forest Products Laboratory, Madison, WI (*13*) (3 x 5 x 1/2 in.).

5. Southern pine.-Southern pine (*Pinus* sp.) sapwood (3 x 5 x 5/8 in.).

6. Western redcedar.–Western redcedar (*Thuja plicata*) heartwood (5 x 5 x 5/8 in.).

7. Ponderosa pine.–Ponderosa pine (*Pinus ponderosa*) sapwood (3 x 5 x 5/8 in.).

8. Red oak.–(*Quercus* sp.) heartwood (3 x 5 x 5/8 in.).

9. Hard maple.-Hard maple (*Acer* sp.) heartwood (3 x 5 x 5/8 in.).

Large Specimens

Southern pine, red oak, Douglas-fir plywood, flakeboard, and ponderosa pine as described above were cut into 6-inch tangential by 10-inch longitudinal specimens with respective radial measurements. The corners, edges, and ends were rounded to a 1/4-inch radius by routing and sanding.

Finishes

A wide variety of wood finishes, both commercially available and laboratory prepared, were evaluated in this study. Appendix A and (8) list the individual finishes with classification by manufacturer according to use. Composition details are shown in both Appendices and in (8). Combinations of these individual finishes were also evaluated (table 7).

Equipment

Belt Sander

An 18-inch belt sander equipped with 100-grit cloth belts was used for the preliminary sanding of all specimens.

Exposure Racks

To achieve optimum vapor transmittance, it was necessary to use exposure racks in which the specimens were able to hang freely. The racks were made of 5/8-inch plywood to fit the appropriate size specimen. Each rack held 18 specimens (fig. 1). Three pairs of specimens (pair = finished plus unfinished, end-matched control) for each one-, two-, and three-coat applications of that finish were hung 5/8-inch apart on screw eyes.

Relative Humidity Rooms

Specimens were conditioned, tested, and weighed in three, walk-in, humidity-temperature rooms; 30 percent RH/80 °F; 90 percent RH/80 °F; and 44 percent RH/72 °F.

Balance

An electronic balance with a 1,200-gram capacity was used. This balance was maintained in the 44 percent RH/72 °F room where the specimens were weighed to the nearest 0.01 gram. Specimens were kept in polyethylene bags while being transported from the 30 and 90 percent RH rooms to the 44 percent RH weighing room.

Methods

Specimen Preparation and Selection

Specimens cut from both lumber and sheets of wood composite products were prepared in the same manner. Each board or sheet was abrasive planed with 50- then 80-grit paper, ripped longitudinally into 3-inch or 6-inch strips that were then cut tangentially into their respective lengths, 5 or 10 inches. The comers, edges, and ends of all specimens were routed to a 1/4-inch radius using a steel carbide router. A 3/32-inch hole was drilled in the center top of each specimen. Final sanding of the specimens began with one quick pass of the face surface and rounding of the routed edges and ends of each specimen on a belt sander. The smoothing of edges, ends and corners was done by hand using 120-grit paper. All specimens were vacuumed using an industrial-size vacuum with a brush attachment, tied into bundles according to board designation, and with end grain exposed preconditioned at 30 percent RH/80 °F for a minimum of 4 weeks. The average conditioned weight per specimen per board was recorded.

For each finish in test, three pairs of end-matched specimens were selected from boards with different densities for each of one-, two-, and three-coat applications. This yielded a total of 18 specimens per finish tested. The three pairs were selected with as large a weight difference as possible to guarantee that each would represent a different range of density being tested (high, medium, or low).

Finish Application

An aluminum hook was screwed into the predrilled hole at the top of each preconditioned specimen following selection for test. One specimen from each pair was labeled as the control and placed on an exposure rack for further conditioning. The other member of the pair was labeled by attaching a cardboard tag to the hook, wrapped in a plastic bag, and taken to the laboratory for finishing.

A 1-1/2-inch nylon or natural bristle brush was used to seal the specimen completely with the finish while holding it by the hook. All ends and edges were coated first and the excess material worked into the face surfaces. Uniform brushing was maintained. Wet weights applied (±0.01 g) were determined by weighing the brush and finish container before and after application. A small selection of finishes was also applied using a 30-second dip. Excess finish was allowed to drip off the specimen and back into the dipping receptacle. Approximate wet weights applied were again recorded. The average finish coverage par coat for three specimens in ft^2/gal was calculated (table 1).

The finished specimens were air dried in a laboratory hood while hanging on an exposure rack for a minimum of 24 hours before applying the next coat or returning them to 30 percent RH/80 °F.

Conditioning, Cycling, and Recycling

Preliminary testing was done to determine the type and extent of exposure to be used in this study. Prior to test, the finished specimens and their matching controls were brought to EMC at 30 percent RH/80 °F. The three pairs of specimens per number of coats for a finish (total of six specimens) were always tested simultaneously. Preferably, one-, two-, and three-coat applications of each finish (total of 18 specimens) were tested together. This procedure eliminated the slight variability in humidity room conditions (±1 pct) for comparing the effectiveness between coats. To minimize additional error, the specimens were individually wrapped in plastic freezer bags for transportation from humidity room to humidity room, thereby preventing exposure to the uncontrollable ambient conditions. The exposure racks used in test were transferred from one humidity room to another along with the bagged specimens. As the same specimens were recycled, identical techniques were used.

Weightng Techniques

Weights recorded in this study were taken from an electronic balance in a 44 percent RH/72 °F room. Exposure of the specimens to these conditions was brief. Weights were taken at days 1, 7, and 14 from the time the specimens entered each humidity.

Tests

Original and Noncontinuous Cycles

The standard and the large specimens of every substrate were all exposed to 90 percent RH/80 °F until MEE was 50 percent or less while in the adsorption phase of the first test cycle. This procedure was designated the original test cycle. The specimens were weighed after 1, 7, and 14 days without exception and every 7 days thereafter while at 90 percent RH/80 °F until MEE reached 50 percent. Once this MEE was reached, the specimens were returned to 30 percent RH/80 °F for re-equilibrating.

Various finishes that performed moderately well to very well on the standard specimens in the original test cycle (table 9) were selected and recycled through two more adsorption/desorption cycles. In each cycle, the specimens were first equilibrated at 30 percent RH/80 °F, then transferred to 90 percent RH/80 °F for 14 days of adsorption and immediately returned to the 30 percent RH/80 °F for 14 days of desorption, followed by re-equilibrating. This form of recycling, equilibrating-testing-equilibrating, is referred to as noncontinuous cycling of specimens.

Continuous Cycles

To monitor the effects of continual humidity changes, three new pairs of duplicate standard specimens for each of one, two, and three coats were prepared using one of the following finishes: an unpigmentad white shellac (finish 23), a pigmented enamel (finish 77), or an aluminum-pigmented paint (finish 65). The specimens were tested for three continuous cycles of 14 days of adsorption at 90 percent RH/80 °F followed by 14 days of desorption at 30 percent RH/80 °F, followed immediately with the next adsorption cycle at 90 percent RH. The specimens began the cycling after being brought to EMC at 30 percent RH/80 °F.

Summary and Conclusions

This report presents results of investigations made to increase knowledge of the degree to which wood can be stabilized in MC with protective finishes. Wood finishes are generally regarded as inefficient stabilizing devices because they merely retard the rate of change in MC without changing the equilibrium that will finally be reached under any given conditions of temperature and humidity. Our work demonstrates that some effective modern finishes limit the changes in MC of wood to a fraction of the changes that take place in unprotected wood.

These studies deal with wood while it is undergoing changes in MC. They are not directly concerned with the equilibrium MC of wood in an environment of constant dampness or dryness because finishes have no effect on such equilibrium. Our interest was in how long it takes the wood, with and without finishes, to change from the initial to the final equilibrium MC or to change some fraction of the difference between the two equilibriums, when the dry wood was exposed to damp air. In other words, we are concerned with variable state not with steady-state conditions. Under variable-state conditions, some factors that are relatively unimportant under steady-state conditions become significant; size of test specimens is an example; the permeability of the finish taken by itself is not enough to determine the results obtained.

The moisture-excluding effectiveness described in our studies is a measure of the moisture gain (from water vapor) of wood protected on all sides by the finish, as compared to the moisture gain of unfinished wood, when both pieces of wood are exposed to a controlled atmosphere of 90 percent RH/80 °F for a given time after being brought to equilibrium at 30 percent RH/80 °F. For example, compared with the unprotected wood, three coats of an aluminum flake-pigmented varnish on ponderosa pine wood were 84 percent effective in controlling moisture vapor movement after 14 days; after 60 days, the MEE was still 51 percent. In contrast, one coat of the pigmented varnish was only 41 percent effective after 14 days while a three-coat penetrating water-repellent finish was only 11 percent effective after 14 days.

The most effective moisture-resistant finishes found for wood were two finishes not usually considered for use on wood. The first, an epoxy sheathing compound (two-component) is essentially an adhesive consisting of 100 percent solids. Most of the commercial finishes used in our studies had some solvent or dispersant ranging from 20 to 50 percent of the weight of the finish. The second finish was molten paraffin wax applied to the wood by dipping (brushing was also used but was not as effective). One coat of the epoxy finish gave an MEE of 54 percent after 14 days; three coats gave an MEE of 91 percent after 14 days, and 70 percent after 60 days. The paraffin wax finish gave an MEE of 95 percent after 14 days and 79 percent after 60 days. When brushed on, the paraffin wax effectiveness was 69 percent after 14 days and 27 percent after 60 days.

With the exception of the two finishes described above, both of which were unpigmented, the wood finishes found most effective in excluding moisture were pigmented products with nonaqueous solvents or dispersants in their compositions such as mineral spirits, alcohol, or turpentine. The MEE of a transparent finish was improved markedly by the addition of pigments. For example, a polyurethane varnish (one-component) was improved by adding 2 lb/gal of an aluminum flake pigment; its three-coat MEE, originally 44 percent after 14 days, rose to 84 percent after the addition. Corresponding MEE values for an unpigmented and pigmented shellac were 42 and 73 percent.

The most effective of the commercially available pigmented finishes were two-component epoxy enamel paints, aluminum flake-pigmented varnishes (already mentioned), a soya-tung alkyd enamel, and a soya-linseed alkyd enamel.

These studies illustrate the MEE of many commercially available finishes for wood ranging from transparent, penetrating-type finishes (sealers, waxes, oils) to pigmented film-forming ones (paints, sealer shellacs, primers). The effects of cycling humidity conditions and different wood substrates are illustrated. Time effects and coating thickness are discussed in detail.

It is clearly shown that any use of paints and other finishes as a moisture vapor retarder for wood must take exposure conditions into account. Good moisture barriers may almost completely insulate wood from short-cycle humidity variations, and at the same time be ineffective against long-term seasonal cycles. Time is an extremely important factor in determining not only the extent but also the character of the response of wood to humidity change.

Few seem to realize the effect that finishes may have on wood warping. In many kinds of goods, the front surface of a wood panel is finished with a coating very effective against moisture movement while no attention is paid to the back or even the edges. When moisture changes take place, the gain or loss of moisture is much greater on the unprotected side than on the finished side and, if the changes occur rapidly, warping is almost sure to result. Such difficulties could be avoided by applying to the back and edge of the wood any coating that will balance the front coating in moisture resistance. This practice would not only reduce the rate of change in MC but permit better equalization of adsorbed moisture. The results of these studies should help in the selection of finishes, whether for the similarity of their moisture vapor resistance or for very high moisture-excluding effectiveness.

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Appendix A
Description of Wood Finishes Used in These MEE Studies

The information in table AI is as supplied by the manufacturer on the container label. A complete description of finishes used in these studies is available (*8*).

Table A1—Finish numbers and description

Finish	Description
	EXTERIOR, UNPIGMENTED, NONAQUEOUS (4 FINISHES TESTED)
1	Two-component, polyurethane, clear gloss finish
2	Phenol-formaldehyde/linseed-tung wood sealer
3	Water repellent (9)
4	Polymeric roof coating
	COMBINATION EXTERIOR/INTERIOR, UNPIGMENTED, NONAQUEOUS (12 FINISHES TESTED)
5	Modified butyl-acrylo-styro epoxy finish
6	Two-component sheathing epoxy (adhesive)
7	Polyurethane gloss varnish
8	Tung oil
9	Two-component polyurethane sealer
10	Two-component polyurethane sealer
11	Linseed oil
12	Linseed oil in mineral spirits
13	Polyurethane gloss varnish
14	Soya alkyd/phenolic/tung gloss varnish (spar)
15	Polyurethane gloss varnish
16	Polyurethane gloss varnish
	INTERIOR, UNPIGMENTED, NONAQUEOUS (19 FINISHES TESTED)
17	Lemon oil furniture polish with silicone
18	Nitrocellulose semigloss lacquer
19	Polyurethane satin varnish
20	Soya alkyd/maleic/China wood oil gloss wood finish
21	Linseed alkyd/maleic/China wood oil satin wood finish
22	Orange shellac
23	White shellac
24	Epoxy gloss varnish
25	Phenolic/tung floor sealer
26	Linseed/phenolic/tung floor sealer
27	Soya alkyd gloss wood finish
28	Alkyd satin wood finish
29	Spray furniture polish (lemon creme, wax, and silicone)
30	Paraffin wax
31	Wallpaper sealer
32	Brazilian Carnuba paste wax
33	Soya epoxy gloss floor and trim sealer
34	Polyurethane satin varnish
35	Nitrocellulose/alkyd lacquer

Table A1—Finish numbers and description—con.

Finish	Description
	EXTERIOR, UNPIGMENTED, AQUEOUS (NO FINISHES TESTED)
	COMBINATION EXTERIOR/INTERIOR, UNPIGMENTED, AQUEOUS (NO FINISHES TESTED)
	INTERIOR, UNPIGMENTED, AQUEOUS (4 FINISHES TESTED)
36	Acrylic gloss varnish
37	Acrylic satin varnish
38	Alkyd varnish
39	Acrylic gloss wood finish
	EXTERIOR, PIGMENTED, NONAQUEOUS (19 FINISHES TESTED)
40	Aluminum-pigmented polyurethane gloss varnish-l
41	Aluminum-pigmented polyurethane gloss varnish-2
42	Aluminum-pigmented polyurethane gloss varnish-3
43	Aluminum-pigmented polyurethane gloss varnish-4
44	Two-component polyurethane gloss paint
45	Soya alkyd flat marine enamel
46	Soya alkyd gloss marine enamel
47	Soya alkyd semigloss marine enamel
48	Alkyd (monopoxy) gloss enamel
49	Soya-linseed alkyd flat undercoat paint
50	Semitransparent linseed oil-based stain (2)
51	Semitransparent linseed oil-based stain
52	Soya alkyd/linseed flat paint
53	Soya alkyd flat primer paint
54	Soya/silicone alkyd gloss enamel
55	Semitransparent linseed oil-based stain
56	Solid color linseed oil-based stain
57	Tall alkyd/soya alkyd gloss house paint
58	Tall maleic alkyd/soya alkyd flat primer paint
	COMBINATION EXTERIOR/INTERIOR, PIGMENTED, NONAQUEOUS (17 FINISHES TESTED)
59	Epoxy resin gloss paint
60	Pigmented Hat shellac
61	Sealer-primer flat finish
62	Phenolic alkyd floor and deck gloss enamel
63	Two-component epoxy/polyamide gloss paint
64	Two-component epoxy/polyamide satin paint
65	Aluminum-pigmented ester gum/vegetable oil metal and masonry paint
66	Aluminum-pigmented petroleum resin utility paint
67	Soya-tung alkyd satin enamel
68	Soya-linseed alkyd gloss floor and deck enamel
69	Two-component epoxy/polyamide gloss enamel
70	Pigmented sealer-primer flat shellac
71	Linseed-phenolic/menhaden-phenolic aluminum paint
72	Linseed-menhaden alkyd gloss paint
73	Two-component polyurethane gloss enamel
74	Soya alkyd gloss enamel
75	Primer/sealer paint

Table A1—Finish numbers and description—con.

Finish	Description
	INTERIOR, PIGMENTED, NONAQUEOUS (3 FINISHES TESTED)
76	Soya alkyd flat paint
77	Soya alkyd gloss enamel
78	Soya-linseed alkyd semigloss enamel
	EXTERIOR, PIGMENTED, AQUEOUS (6 FINISHES TESTED)
79	Acrylic latex flat primer paint
80	Acrylic latex Hat house paint-1
81	Acrylic latex flat house paint-2
82	Acrylic latex flat house paint-3
83	Acrylic latex solid color stain
84	Acrylic latex/soya alkyd flat house paint
	COMBINATION EXTERIOR/INTERIOR, PIGMENTED, AQUEOUS (2 FINISHES TESTED)
85	Acrylic latex/epoxy ester concrete floor paint
86	Pigmented acrylic shellac primer
	INTERIOR, PIGMEMED, AQUEOUS (5 FINISHES TESTED)
87	Vinyl acetate-acrylic latex enamel undercoat
88	Acrylic latex satin enamel
89	Acrylic latex flat enamel
90	Butadiene-styrene latex flat primer paint
91	Vinyl acrylic latex flat wall paint

Appendix B
Composition of Finishes[a]

This listing provides quantitative measures of the Composition of the 91 finishes investigated in this study, which are grouped according to their finish characteristics.

Table B1.—Composition of finishes[a].

Finish	Surface[b]	Finish density	Solids		Total pigment	Total resin	Total oil
			Meas-ured	Manu-fac-turer			
		Lb/gal	*Pct*				
			EXTERIOR, UNPIGMENTED, NONAQUEOUS				
1	Gloss	8.22	43.6	34.7	0.0	34.7	0.0
2	Satin	7.14	20.3	22.5	0.0	10.4	12.1
3	—	6.71	12.6	10.9	0.0	9.8	0.0
4	—	7.52	31.5	38.4	6.9	26.2	0.0
			COMBINATION EXTERIOR/INTERIOR, UNPIGMENTED, NONAQUEOUS				
5	Flat	8.39	29.0	—	0.0	29.0	0.0
6	Goss	8.80	99.0	—	0.0	99.0	0.0
7	Gloss	7.51	50.7	47.5	0.0	47.5	0.0
8	—	7.79	99.9	99.9	0.0	0.0	99.9
9	Gloss	8.24	46.2	40.0	0.0	40.0	0.0
10	Gloss	7.98	40.7	40.0	0.0	40.0	0.0
11	—	7.78	99.9	99.9	0.0	0.0	99.9
12	—	7.11	52.1	50.0	0.0	0.0	50.0
13	Gloss	7.63	53.5	49.5	0.0	49.0	0.0
14	Gloss	7.55	59.0	54.3	0.0	47.6	6.7
15	Gloss	7.37	55.3	45.6	0.0	45.3	0.0
16	Gloss	7.52	54.1	52.0	0.0	52.0	0.0
			INTERIOR, UNPIGMENTED, NONAQUEOUS				
17	—	—	—	—	0.0	—	—
18	Satin	7.59	19.0	21.5	0.0	21.5	0.0
19	Satin	7.74	51.3	44.8	0.0	44.8	0.0
20	Gloss	7.43	43.9	40.3	0.0	38.5	1.8
21	Satin	7.75	44.7	39.1	8.0	28.4	2.7
22	—	7.54	31.0	30.7	0.0	30.7	0.0
23	—	7.52	30.0	30.7	0.0	30.7	0.0
24	Gloss	7.18	42.7	40.8	0.0	39.6	0.0
25	—	7.04	37.2	33.6	0.0	13.3	20.3
26	—	7.32	52.0	48.3	0.0	41.1	7.2
27	Gloss	7.50	43.1	41.5	0.0	41.5	0.0
28	Satin	7.20	33.7	29.5	7.6	21.9	0.0
29	—	—	4.5	—	0.0	—	—
30	—	—	—	99.9	0.0	0.0	0.0
31	—	8.47	19.0	—	0.0	—	—
32	—	—	—	—	0.0	—	—
33	Gloss	7.02	30.4	31.5	0.0	30.0	0.0
34	Satin	7.41	46.7	45.0	2.0	43.0	0.0
35	Gloss	7.60	25.5	31.0	0.0	25.4	2.5

Table B1.—Composition of finishes[a]—con.

Finish	Surface[b]	Finish density	Solids: Meas-ured	Solids: Manu-fac-turer	Total pigment	Total resin	Total oil
		Lb/gal	---------------------*Pct*---------------------				
INTERIOR, UNPIGMENTED, AQUEOUS							
36	Gloss	8.63	36.7	28.2	0.0	28.2	0.0
37	Satin	8.75	38.0	29.5	1.5	28.0	0.0
38	Gloss	9.33	44.4	44.0	4.0	40.0	0.0
39	Gloss	8.88	39.6	37.0	0.0	33.0	0.0
EXTERIOR, PIGMENTED NONAQUEOUS							
40	Gloss	8.32	63.3	54.0	13.8	40.1	0.0
41	Gloss	8.29	63.8	54.0	13.5	39.2	0.0
42	Gloss	8.28	62.6	54.0	13.5	39.2	0.0
43	Gloss	8.30	64.5	54.0	13.6	39.5	0.0
44	Gloss	10.32	63.5	52.1	42.1	29.4	0.0
45	Flat	10.58	66.4	61.4	42.1	19.1	0.0
46	Gloss	9.66	69.2	65.7	28.6	36.7	0.0
47	Satin	10.73	71.8	70.2	40.5	29.4	0.0
48	Gloss	9.74	63.2	61.1	30.0	29.2	0.0
49	Flat	11.74	75.3	70.9	52.7	16.6	0.0
50	—	7.96	75.5	75.7	8.4	0.0	61.0
51	—	7.90	77.9	—	—	—	—
52	Flat	10.57	73.0	62.1	42.2	13.5	6.4
53	Flat	10.61	70.0	63.7	44.0	19.7	0.0
54	Gloss	9.49	65.1	62.5	25.6	35.1	0.0
55	—	6.91	20.5	—	—		
56	—	9.48	59.6	—	—	—	—
57	Gloss	9.10	67.3	65.0	26.0	38.0	0.0
58	Flat	11.40	78.5	74.0	45.0	28.0	0.0
COMBINATION EXTERIOR/INTERIOR, PIGMENTED, NONAQUEOUS							
59	Gloss	9.69	43.0	41.1	18.1	23.0	0.0
60	Flat	9.92	53.7	53.2	31.7	21.5	0.0
61	Flat	10.14	63.3	71.2	40.0	30.0	0.0
62	Gloss	7.88	57.0	83.4	24.0	59.4	0.0
63	Gloss	10.27	64.1	61.0	28.3	32.7	0.0
64	Satin	10.66	65.6	65.0	28.3	32.7	0.0
65	Satin	8.09	61.0	59.2	19.3	4.8	35.1
66	Gloss	7.97	56.0	57.4	14.4	43.0	0.0
67	Satin	12.36	79.3	73.9	50.8	23.1	0.0
68	Gloss	9.11	66.8	56.4	24.9	31.5	0.0
69	Gloss	10.25	63.0	58.4	24.1	34.3	0.0
70	Flat	9.90	52.8	53.4	34.0	19.4	0.0
71	Gloss	7.86	47.0	49.3	13.0	36.3	0.0
72	Gloss	9.23	60.0	60.9	26.7	34.2	0.0
73	Gloss	10.10	63.7	—	—	—	0.0
74	Gloss	9.45	67.3	61.5	26.9	34.6	0.0
75	Flat	10.30	55.6	—	—	—	—
INTERIOR, PIGMENTED, NONAQUEOUS							
76	Flat	12.46	72.2	69.2	61.5	7.7	0.0
77	Gloss	10.39	71.1	69.5	34.6	34.9	0.0
78	Satin	10.74	68.3	69.0	46.2	22.8	0.0
EXTERIOR, PIGMENTED, AQUEOUS							
79	Flat	9.76	52.0	51.0	21.0	28.0	0.0
80	Flat	10.93	53.0	50.0	29.0	19.0	0.0
81	flat	11.02	58.7	57.2	35.6	21.6	0.0
82	Flat	11.28	59.1	57.5	37.4	20.1	0.0
83	—	10.43	45.1	—	—	—	—
84	Flat	11.27	52.2	50.0	33.0	17.0	0.0
COMBINATION EXTERIOR/INTERIOR, PIGMENTED AQUEOUS							
85	Satin	10.76	56.0	49.4	27.9	21.5	0.0
86	Flat	10.65	52.3	50.0	29.6	20.4	0.0
INTERIOR. PIGMENTED, AQUEOUS							
87	Flat	11.20	51.4	55.7	41.3	14.4	0.0
88	Satin	10.60	51.1	49.2	26.6	22.6	0.0
89	Flat	11.03	53.5	48.0	28.2	19.8	0.0
90	Flat	10.67	56.0	57.0	31.9	23.1	0.0
91	Flat	11.09	51.0	49.5	38.0	11.5	0.0

[a]For names of finishes and additional composition information see(*8*).

[b]Satin = Semigloss.

Appendix C Adjustment of MEE Values for Wood Density

If an investigator wishes to compare finish performance precisely yet knows that the effect of wood density has not been controlled, then one way to take account of density is by an analysis of covariance. A simpler approach, in the same spirit as analysis of covariance, involves inserting an emperical factor in the formula for MEE. For example, the small ponderosa pine specimens all have the same volume. We inserted a correction factor in the change-in-weight ratio that appears in the MEE formula. The unadjusted MEE (percentage) at time t is given by:

$$MEE_t = (1 - \Delta W_{Tt}/\Delta W_{Ut}) \times 100$$

where ΔW_{Tt} is the change in weight of the finished specimen between time zero and time t and ΔW_{Ut} is the corresponding change in weight of the matched control specimen. If $R_t = \Delta W_{Tt}/\Delta W_{Ut}$ and $A = W_{UTo}/W_{ref}$ where W_{UTo} is the equilibrium weight of the control specimen at time zero and W_{ref} is some reference weight for the uncoated specimens, then adjusted MEE (percentage) is given by:

$$MEE_{adj \cdot t} = (1 - R_t \cdot A) \times 100$$

For a reference weight, we used $\overline{W}_{Uto}$, the average at time t_o of the 852 uncoated specimens in this part of the study. Figures 11 and 12 are scatter plots respectively of the unadjusted MEE_{14} values plotted against wood density (three replicate specimens) for each of 9 finishes. Comparison of the figures shows that adjustment eliminates much of the dependence of MEE on density.

A simple linear relationship (with average = a and slope = b) seems to characterize the dependence of ordinary MEE on density when we exclude the poor finishes. We used this equation to relate MEE_t to density d for k coats:

$$MEE_{tkij} = a_{tki} + b_{tk}(d_{tokij} - \overline{d}_{tok})$$

where i is finish number and j is replicate number (1, 2, or 3). Then MEE_{tkij} is MEE_t with k coats of finish i for the j-th replicate; a_{tki} is the average MEE_t with k coats of finish i when the corresponding density is at its average value; b_{tk} is the slope of MEE_t on “centered” density at time t with k coats; d_{tokij} is the density at time zero of the control specimen before k coats of the i-th finish are applied to the j-th replicate matching treated specimen; $\overline{d}_{tok}$ is the average density at time zero over all finishes and replicates having k coats. Specimens with any good finish of k coats at time t fall on one of a set of parallel lines when MEE is plotted versus wood density. The particular finish of the specimen determines on which line the specimen falls.

Table Cl shows the results of fitting the above equation to data from good finishes. (The table gives our definition of the “good” finishes used in fitting the equation. Thus, a good l-coat finish has MEE_{14} at least 25 pct for all three replicates.) As the equation indicates, we fitted a separate regression for each time and coat combination, for time = 1, 7, and 14 days and coats = 1, 2, and 3. The number of observations used depends on the number of good finishes for each coat, and thus varies with coat number. For example, for 1 coat, we have 13 good finishes, and three replicates for each finish; thus we have n = 39 observations for our regression for t = 1 day, t = 7 days, and t = 14 days. Each yields the same picture: 13 noncoincident parallel levels. With these 13 levels plus one common slope we have p = 14 parameters. Because p/n is about 1/3 in each of the regressions, we report an R^2 that is adjusted for the relatively large number of parameters.

The table shows two patterns involving the b_{tk} defined in the above equation. First, for any particular number of coats k, the slope b_{tk} gets steeper as time increases from t = 1 to t = 14 days. This pattern follows from the definition of MEE_t: for any particular good finish, the ratio R_t tends to be larger for low-density specimens and smaller for high-density specimens. We see this tendency in R_t because the denominator W_{Ut} increases linearly with density while the numerator W_{Tt} remains relatively unaffected by density. Second, for any particular time t, the common slope gets smaller as the number of coats increases. This pattern makes sense because the thicker the finish layer, the less effect the wood specimen has as a sponge to draw in water-poor sponges and good sponges alike will be hindered by a thick coating.

The values of R^2 reported in table Cl should be viewed with a bit of caution. If there were no relationship between wood density and MEE but very good finishes were applied to high-density specimens and merely good finishes were applied to low-density specimens, one could still obtain a high R^2. We examined plots and regressions of MEE versus density for each finish and for days 1, 7, and 14. The general comments made above about the common slope regression models appear valid in light of these individual finish results.

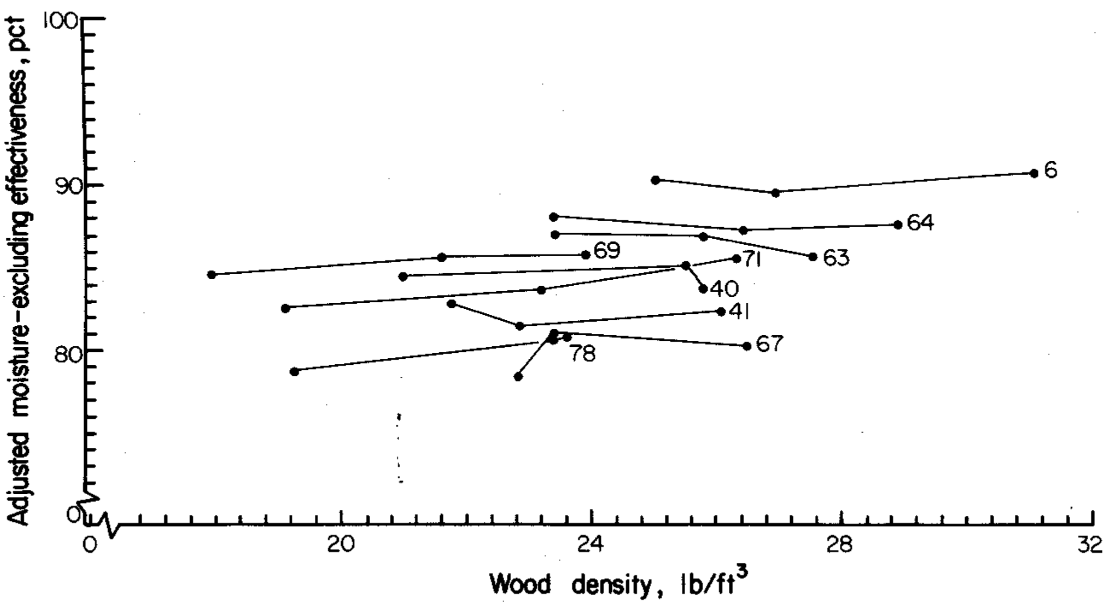

Figure 11.—Moisture-excluding effectiveness (MEE) of 9 finishes on ponderosa pine sapwood (specimens of low, medium, and high density) after 14 days at 90 percent relative humidity and 80 °F.

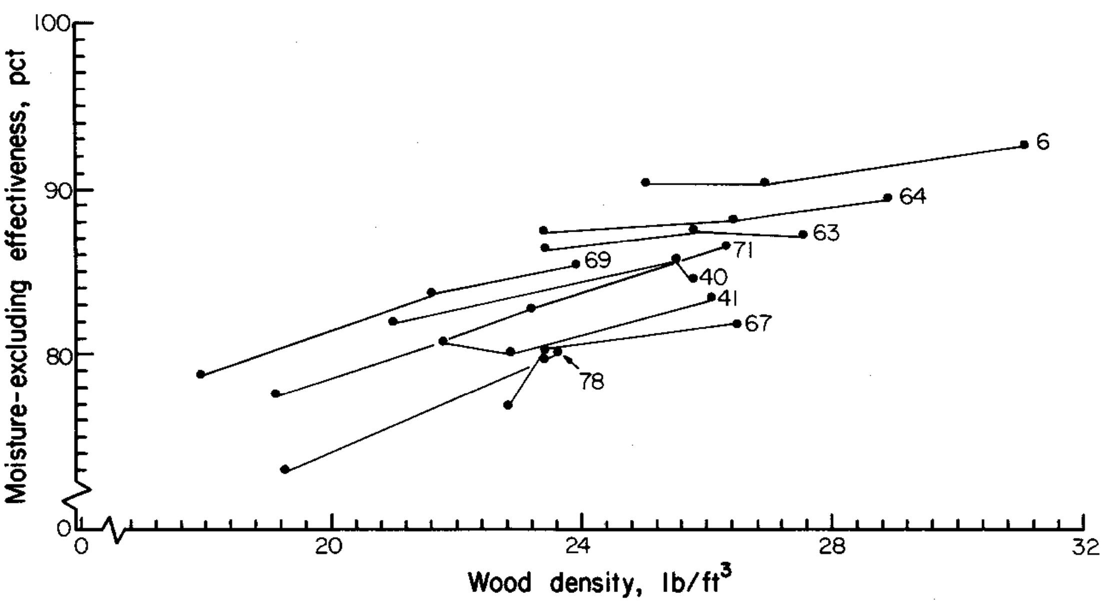

Figure 12.—Adjusted moisture-excluding effectiveness (MEE) of 9 finishes on ponderosa pine sapwood (specimens of tow, medium, and high density) after 14 days at 90 percent relative humidity and 80 °F.

Table C1.—Regression of moisture-excluding effectiveness (MEE) on wood density for three thicknesses of coat and three times of exposure

Duration of test	1 Coat[a]			2 Coats[a]			3 Coats[a]		
	Slope = b_{t1} (standard error)	R^2_{adj} [b]	s[c]	Slope = b_{t2} (standard error)	R^2_{adj}	s	Slope = b_{t3} (standard error)	R^2_{adj}	s
Days									
1	0.34 (0.158)	39	1.94	0.14 (0.025)	96	0.45	0.10 (0.022)	94	0.36
7	1.80 (0.320)	80	3.92	1.00 (0.084)	97	1.53	0.69 (0.058)	97	0.98
14	2.46 (0.355)	82	4.34	1.67 (0.135)	96	2.45	1.13 (0.010)	98	1.50

[a]1 coat: 39 observations, 3 replicates of 13 good finishes (MEE ≥ 25 pct for every replicate, excluding finishes 1 and 6)
2 coats: 60 observations, 3 replicates of 20 good finishes (MEE ≥ 37 pct for every replicate, excluding finish 6)
3 coats: 63 observations, 3 replicates of 21 good finishes (MEE ≥ 50 pct for way replicate, excluding finishes 1 and 6)
[b]Adjusted correlation coefficient (R^2) is related to ordinary R^2 by this equation:

$$R^2_{adj} = (n - 1)R^2/(n - p) - (p - 1)/(n - p)$$

where n = number of observations in the regression and p = number of parameters fitted.

C_s is the square root of the mean square error of regression and gives a summary measure of variability of regression. Values of s within the same column are directly comparable.

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