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REDUCING VOC EMISSIONS IN THE FURNITURE AND CABINETS INDUSTRIES: AN OPPORTUNITY FOR HYBRID COATING SYSTEMS

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Three hybrid systems were compared to a solvent-based low-VOC system. The goal of the project was to determine if the hybrid systems met the requirements of the kitchen cabinet and furniture industries. Adhesion of each system to the substrate was first evaluated, and significant differences were recorded. Subsequently, resistance to heat and moisture was evaluated using hot box and hot and cold check tests. These tests indicated that the experimental systems generally performed relatively well in terms of thermal resistance, but the appearance of those prepared from solvent-borne sealers and lacquers were less stable. The chemical resistance of these systems was also studied. The ability of the finish to withstand the effects of substances typically found in a kitchen was tested, as was their resistance to detergents and water. All the systems performed very well in vertical testing. Volatile organic compound emissions were finally measured after conditioning times of 3 and 21 days. These tests showed that the different systems behaved quite differently. The systems prepared with solvent-borne sealers and lacquers produced a high level of VOCs at the beginning of the test, with a rapid decrease thereafter, while the opposite was observed in systems based on water-borne sealers and lacquers.

INTRODUCTION

The furniture and kitchen cabinet industries are facing a challenge with respect to finishes. Regulations on Volatile Organic Compounds (VOC) are becoming tighter in many countries. European Union regulations limit VOCs to 140 g/L and 600 g/L, respectively, for water-borne and solvent-borne one-pack performance coatings (Anonymous 2004). In Canada, regulations are under consideration for both architectural and industrial coatings. For architectural coatings only, emissions are currently limited to 680 g/L for clear brushing lacquers, and 550 g/L for all other lacquers, including lacquer and sanding sealers (Anonymous 2008). In the USA, the California Air Board Regulation (CARB) regulation, which has been adopted by many states, restricts VOCs to a maximum of 275 g/L for topcoats and 250 g/L for stains.

The coating industry has suggested different strategies to help furniture and cabinet manufacturers to meet these regulations. On the basis of their broad experi-ence with solvent-borne coatings over several decades, the woodworking industries

and consumers expect to meet these new VOC requirements and maintain the same coating quality as when using solvent-borne coatings.

It appears that a low VOC emitting coating should meet three criteria: 1) Satisfy current or expected VOC regulations (low emission); 2) Maintain adhesion properties; and 3) Maintain the appearance of traditional solvent-borne coatings. These three criteria were applied to four coating strategies (Table 1). The first strategy involved a low-emission solvent-based system consisting of a solvent stain, a solvent sealer and a solvent lacquer. The second strategy involved a water-borne/solvent-borne system consisting of a water-borne stain, a solvent-borne sealer and a solvent-borne lacquer. The third strategy involved a solvent-borne/water-borne system consisting of a solvent-borne stain combined with two water-borne sealer layers and one water-borne lacquer layer. The fourth strategy was similar to the third one but with only one water-borne sealer coat applied. These are called hybrid coating systems.

Table 1. Description of the Hybrid Coating Systems Used in this Study *

	System 1	System 2	System 3	System 4
System description	SB stain SB sealer SB lacquer	WB stain SB sealer SB lacquer	SB stain WB sealer WB sealer WB lacquer	SB stain WB sealer WB lacquer
Cost comparison (order of magnitude)	1	0.9-0.95	1.5	1.10-1.15

* SB = solvent-based; WB = water-based

The objective of the study was to assess these three hybrid coating systems in terms of VOC emissions, adhesion performance and appearance, and to compare them to a low VOC emitting solvent-based system.

MATERIALS AND METHODS

Wood material was prepared as follows. Edge-glued panels where manufactured with yellow birch wood, a porous hardwood with a nominal density of 559 kg/m^3 (Jessome 2000). The panels were conditioned at 20°C and 50% relative humidity (RH) until equilibrium (constant mass). Thirty panel replications were manufactured. The panels were planed and sanded in an SCM belt sander using the following sanding paper grit sequence: P100, P120, and P150. The panels were then sawn to provide four 15 by 15-cm boards, one for each coating system. Final sanding was performed with a Sioux orbital sander (12,000 RPM) with a P180 sand paper just before coating. The sealer was sanded with a P320 sandpaper.

The stains were applied with a pad to obtain a wiped color. The sealers and lacquers were applied with a Falconi reciprocator, which produced a constant film thickness. The water-borne sealer used in these tests was an acrylic, and the solvent-borne one was a nitro-vinyl. Pre-catalyzed acrylic and post-catalyzed lacquers were used respectively as water- and solvent-borne lacquers.

COV emissions were determined at 3 days and 21 days after coating application using the test method described in ASTM Standard D5116, *Standard Guide for Small Scale Environmental Chamber Determination of Organic Emissions from Indoor Materials/Products*. The method uses a small environmental chamber

(0.053 m³). The air volume was replaced once per hour with filtered and purified air. After 24 hours, the air was sampled with a TENAX® Pyrex tube containing a diphenylene oxide-based porous polymeric resin. The resin captures a wide variety of COVs that can be released under heat. Analyses were conducted with a GS/MS and compound peaks were compared by means of a NBS/NHI spectra database.

Adhesion was determined with two test methods: ASTM D 4541-*Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers* and ASTM D3359-*Standard Test Methods for Measuring Adhesion by Tape Test*. The first method uses aluminum dollies glued onto the coated surface; the ultimate load under perpendicular traction is recorded. The second method uses a multiblade knife. The surface is scratched perpendicularly with the knife and a standardized tape is applied over the scratch pattern. The coating pull-out pattern is then compared with a chart provided in the test method.

With furniture and cabinets, appearance is critical. Two test methods were used to determine to what extent appearance was affected when the specimens were exposed to different climatic conditions. The hot box test was suggested by the Kitchen Cabinet Manufacturers Association (ANSI/KCMA A161.1-2000). The coated samples are placed in an oven at 50°C and 70% RH for 24 hours. At the end of this period, any discoloration, blister, or other defect are recorded. ANSI/KCMA Standard A161.1-2000 also defines the other test method, whereby the specimens were submitted to the following cycle: 50°C and 70 % RH for one hour, back to ambient temperature, and one hour at -20°C; this cycle being repeated five times. For both tests, ANSI/KCMA A161.1-2000 suggests a visual inspection, but, in this research, changes to appearance were quantified through gloss and color measurements. Gloss was determined with a BYK Gardner micro-TRI-gloss at 60°. Color was determined with a BYK Gardner color-guide 0/45, in the CIELAB coordinate system.

RESULTS AND DISCUSSION

Total VOC Emission Factors

Tables 2 and 3 present the detailed and the total VOC emissions measured after 3 and 21 days following application of the coating systems and conditioning at 23°C and 50% RH. After 3 days, Systems 1 and 2 led to higher total emission factors (TEFs) than Systems 3 and 4, a result that was expected, given that Systems 1 and 2 were prepared solvent-borne sealer and lacquers. After 21 days, Systems 1 and 2 yielded lower TEFs than Systems 3 and 4. This result was due not only to lower TEFs in Systems 1 and 2, but also to greater TEFs in Systems 3 and 4. This was unexpected and warranted further analysis. Systems 1 and 2 were solvent-borne, and the solvents are known to evaporate quickly after application. Such evaporation was fast enough to result in a low TEF (231 μg/m².hr) after 21 days of conditioning (Table 1 and Fig.1). In water-borne systems (3 and 4), some polar low-evaporation-rate solvents (i.e.: 2-propanol 1-butoxy and 1-(2-methoxy propoxy)2-propanol) were used with water, which slowed down the evaporation process, explaining the higher TEFs obtained for these systems after 21 days of conditioning. These low-evaporation-rate solvents are used in order to favor the coalescence of the coating films. TEF values after 3 and 21 days of conditioning are shown in Fig. 1. All the systems were air dried, but for the hybrid systems (Systems 2, 3, and 4), a convection drying phase would have helped to

decrease TEFs after 21 days by accelerating the evaporation of low evaporation rate solvents in water-borne components.
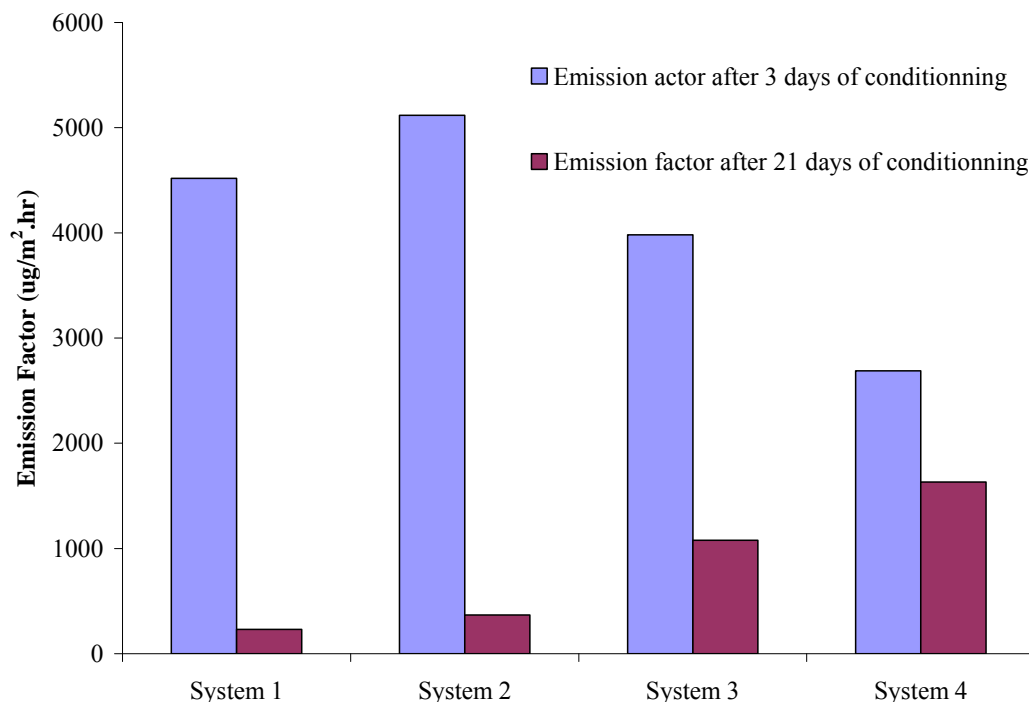

Fig. 1. Emission factors measured after 3 and 21 days for the four systems

Adhesion Performance

The selecting of a hybrid system to reduce VOC emissions should meet industry and market requirements, including those relating to coating adhesion. The test methods described in ASTM D 4541-*Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers* and ASTM D3359-*Standard Test Methods for Measuring Adhesion by Tape Test* were used to assess this property. Figure 4 displays the average loads needed to pull off aluminum dollies glued onto the coated surfaces with an epoxy adhesive. The figure shows that the full solvent-borne system (System 1) yielded the best adhesion to the wood substrate. As all layers are solvent-borne and prepared with the same organic solvents, they are highly compatible. The second best was System 2, in which only the stain was water-borne. The third was System 3, which combined a solvent-borne stain, two water-borne sealer coats and one lacquer coat. System 4, consisting of a solvent-borne stain, a water-borne sealer and a water-borne lacquer layer, yielded the lowest adhesion value.

An ANOVA conducted on adhesion values confirmed the distinction between the two groups (Table 4), i.e.: the systems with a solvent-borne sealer and a solvent-borne lacquer (Systems 1 and 2), and the systems with a water-borne sealer and water-borne lacquer (Systems 3 and 4). This observation does not agree with the results of Hernandez and Cool (2008), who found better adhesion with water-borne systems than with solvent-borne ones. However, this may explained by the fact that they worked with a complete water-based system and not with hybrid systems.

Table 2: Volatile Organic Compounds Detected after 3 Days of Conditioning

Volatile organic compounds detected**	System #1		System #2		System #3		System #4	
	Concentration	Emission factor	Concentration	Emission factor	Concentration	Emission Factor	Concentration	Emission factor
	µg/m³	µg/m².hr	µg/m³	µg/m².hr	µg/m³	µg/m².hr	µg/m³	µg/m².hr
Acetic acid	<2.0	n.a.	4.0	9.8	2.2	5.3	2.9	7.0
1-Propanol,2-methyl	5.37×10^2	1.30×10^3	5.14×10^2	1.26×10^3	- - -	- - -	- - -	- - -
1-Butanol	1.03×10^3	2.47×10^2	8.47×10^2	2.07×10^3	<2.0	n.a.	<2.0	n.a.
Toluene	9.4	22.7	16.8	41.0	4.2	9.9	3.7	8.9
Acetic acid, butyl ester	72.7	1.75×10^2	1.29×10^2	3.15×10^2	12.7	30.1	13.1	31.3
1-Propanol, 2-ethoxy-	- - -		2.53×10^2	6.18×10^2	- - -	- - -	- - -	- - -
Cyclotrisiloxane, hexamethyl-	5.8	14.0	7.0	17.2	<2.0	n.a.	2.4	5.8
Ethylbenzene	- - -		2.6	6.5	<2.0	n.a.	<2.0	n.a.
m-p xylene	4.6	11.0	11.6	28.4	3.0	7.2	2.9	6.9
o-xylene	<2.0	n.a.	3.8	9.4	<2.0	n.a.	<2.0	n.a.
Ethanol, 2-butoxy-	4.7	11.2	<2.0	n.a.	4.01×10^2	9.51×10^2	1.67×10^2	3.99×10^2
2-Propanol-1-butoxy	- - -	- - -	- - -	- - -	2.17×10^2	5.16×10^2	1.70×10^2	4.08×10^2
Trisiloxane, octamethyl-	<2.0	n.a.	<2.0	n.a.	- - -	- - -	<2.0	n.a.
2-Propanol, 1-(2-methoxy-1-methylethoxy)-	- - -	- - -	- - -	- - -	3.03×10^2	7.20×10^2	1.42×10^2	3.39×10^2
2-Propanol, 1-(2-methoxypropoxy)-	- - -	- - -	- - -	- - -	1.78×10^2	4.23×10^2	80.4	1.92×10^2
Cyclotetrasiloxane, octamethyl-	9.2	22.2	11.7	28.6	20.4	48.3	18.6	44.4
o-cymene	2.8	6.6	- - -	- - -	- - -	- - -	- - -	- - -
Tetrasiloxane, decamethyl-	6.9	16.6	- - -	- - -	- - -	- - -	- - -	- - -
Cyclopentasiloxane, decamethyl-	85.1	2.05×10^2	6.1	15.0	- - -	- - -	- - -	- - -
Pentasiloxane, dodecamethyl-	17.4	42.0	76.2	1.86×10^2	- - -	- - -	- - -	- - -
Cyclohexasiloxane, dodecamethyl-	<2.0	n.a.	17.5	42.8	- - -	- - -	- - -	- - -
Hexasiloxane, tetradecamethyl-	14.2	34.3	2.4	5.9	- - -	- - -	- - -	- - -
Total Unknown Compounds	79.0	1.90×10^2	1.87×10^2	4.56×10^2	2.66×10^2	6.31×10^2	3.45×10^2	8.26×10^2
Total Volatile Organic Compounds	**1.87×10^3**	**4.52×10^3**	**2.09×10^2**	**5.12×10^3**	**1.68×10^3**	**3.98×10^3**	**1.12×10^3**	**2.69×10^3**

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Table 3. Volatile Organic Compounds Detected after 21 Days for the Four Systems

Volatile Organic Compounds detected	System #1		System #2		System #3		System #4	
	Concentration	Emission Factor	Concentration	Emission Factor	Concentration	Emission Factor	Concentration	Emission Factor
	µg/m³	µg/m².hr	µg/m³	µg/m².hr	µg/m³	µg/m².hr	µg/m³	µg/m².hr
Acetic acid	<2.0	n.a.	2.4	5.8	2.7	6.3	4.2	10.0
1-Propanol,2-methyl	15.4	36.4	6.6	15.8	- - -	- - -	- - -	- - -
1-Butanol	41.5	98.1	25.5	61.2	3.2	7.6	<2.0	n.a.
1-Propanol, 2-ethoxy-	- - -	- - -	59.3	1.43×10^2	- - -	- - -	- - -	- - -
Toluene	3.0	7.0	4.7	11.4	<2.0	n.a.	2.5	5.9
Acetic acid, butyl ester	18.2	42.9	23.1	55.5	5.1	12.1	12.6	29.8
Cyclotrisiloxane, hexamethyl-	2.0	4.8	2.5	6.1	<2.0	n.a.	<2.0	n.a.
Ethylbenzene	- - -	- - -	- - -	- - -	<2.0	n.a.	<2.0	n.a.
m,p-xylene	<2.0	n.a.	2.7	6.4	<2.0	n.a.	<2.0	n.a.
o-xylene	<2.0	n.a.	<2.0	n.a.	<2.0	n.a.	<2.0	n.a.
Ethanol, 2-butoxy-	<2.0	n.a.	<2.0	n.a.	1.47×10^2	3.47×10^2	82.9	1.96×10^2
2-Propanol-1-butoxy					48.1	1.14×10^2	52.2	1.24×10^2
Cyclotetrasiloxane, octamethyl-	2.8	6.6	3.9	9.4	7.7	18.1	24.8	58.8
o-cymene	<2.0	n.a.	- - -	- - -	- - -	- - -	- - -	- - -
Tetrasiloxane, decamethyl-	<2.0	n.a.	- - -	- - -	- - -	- - -	- - -	- - -
2-Propanol, 1-(2-methoxy-1-methylethoxy)-	- - -	- - -	- - -	- - -	45.9	1.08×10^2	53.7	1.27×10^2
2-Propanol, 1-(2-methoxypropoxy)-	- - -	- - -	- - -	- - -	24.1	56.9	5.6	13.3
Cyclopentasiloxane, decamethyl-	10.8	25.4	9.2	22.2	- - -	- - -	- - -	- - -
Pentasiloxane, dodecamethyl-	<2.0	n.a.	<2.0	n.a.	- - -	- - -	- - -	- - -
Cyclohexasiloxane, dodecamethyl-	<2.0	n.a.	<2.0	n.a.	- - -	- - -	- - -	- - -
Hexasiloxane, tetradecamethyl-	<2.0	n.a.	<2.0	n.a.	- - -	- - -	- - -	- - -
Total Unknown Compounds	4.1	9.8	13.5	32.4	1.04×10^2	2.46×10^2	**2.80×10^2**	**6.64×10^2**
Total Volatile Organic Compounds	**97.8**	**2.31×10^2**	**1.53×10^2**	**3.69×10^2**	**4.57×10^2**	**1.08×10^3**	**6.89×10^2**	**1.63×10^2**

Table 4. Coating-to-Substrate Adhesion According to ASTM D 4541, and Waller-Duncan Grouping

System	Adhesion (MPa)	Waller-Duncan grouping
1	4.4±1	A
2	4.2±0.9	A
3	2.5±0.9	B
4	2.1±0.4	B

In the present study, all systems were hybrid, and at least one component was solvent-borne. According to the results of the ANOVA, the use of a solvent-borne stain with a water-borne sealer and lacquer resulted in a loss of adhesion as compared with a full solvent system (1) and a water-borne stain with solvent-borne sealer and lacquer (2). Charron (1998) reported that adhesion problems could occur when water-based products are applied on solvent-based products. In order to limit this problem, drying time should be increased or a drying oven should be use.

Appearance Performance

In the kitchen and cabinet industry, the appearance of the finished product is the signature of the product. It is especially important in upper kitchen cabinets, as they stand at eye level. Hybrid coatings should therefore meet consumer expectations in the short term as well as over time, when exposed to different climatic conditions.

A visual inspection before and after the hot box test (ANSI/KCMA A161.1-2000) did not reveal any major problem, but a closer assessment of the specimens with a colorimeter and a glossmeter provided more significant results. The chromatic component b* and the total color variation ΔE are shown in Table 5. In the CIELab coordinate system, the b* color component is represented in the blue-yellow axis. The yellowing characteristic of finishing systems is a well known issue, and the use of a hybrid system should not increase yellowing over that occurring with solvent-borne systems. Table 5.5 indicates the variation of b* (Δb) observed before and after the hot box test. Δb was found to be highest with System 2 (2.29), and this result was statistically different from those obtained with the other systems. The solvent-borne system (System 1) yielded the second highest Δb (1.41), and this result was statistically different from those relating to Systems 2, 3 and 4. The lowest Δb was observed for Systems 3 and 4, which were not statistically different from each other but statistically different from Systems 1 and 2. Systems 3 and 4 involved a water-borne sealer and lacquer while Systems 1 and 2 relied on a solvent-borne sealer and lacquer. Solvent-borne lacquers, especially those using aromatic solvents, are known to be more prone to yellowing than water-borne lacquers. Total color variation (ΔE) is the vector representation of all the chromatic components (a*, b* and L*). Table 5.6 presents ΔE for all the systems after hot box testing. It includes the same observations as for Δb, and confirms the critical weight of the b* variation in total color change. It is generally assumed that a normal person cannot see differences between two samples if ΔE is less than 2. Colorists however can perceive differences between two samples from a ΔE of 0.5.

Table 6 shows the loss in gloss measured after the hot box test for all four coating systems. Again, solvent-borne sealers and lacquers (Systems 1 and 2) behaved similarly, showing significant gloss loss (25.9 % and 26.8 % respectively), while gloss loss with water-borne sealers and lacquers remained light (0.6 % and 2.12% respectively for Systems 3 and 4).

Table 5. Color Variation (b* and ΔE) after Hot Box Test (KCMA/ANSI 161.1) and Waller-Duncan Grouping

System	Δb	Waller-Duncan grouping	System	ΔE	Waller-Duncan grouping
2	2.29	A	2	2.34	A
1	1.41	B	1	1.59	B
3	0.27	C	3	0.50	C
4	0.33	C	4	0.87	C

Table 6. Gloss Loss after Hot Box Testing (KCMA/ANSI A161.1 2000)

System	Before	After	Gloss loss (%)
1	42.04	31.15	25.90
2	41.45	30.33	26.83
3	60.45	60.08	0.61
4	56.68	55.44	2.19

Coating appearance integrity was also measured by means of the hot and cold check test (KCMA/ANSI 161.1-2000), with colorimetry being used to measure variations in the b* color component and total color variation (ΔE) after the test. Gloss loss was also evaluated. Systems 1 and 2 were found to be statistically similar with respect to Δb, and Systems 1, 3 and 4 were also determined to be statistically similar. All the systems in this last group were using a solvent-borne stain. As regards total color variation (ΔE), the differences observed between all the systems using a solvent-borne stain were found to be statistically non-significant. ΔE for this group was statistically lower than for System 2, which used a water-borne stain. This suggests that a hybrid system may take advantage of the color obtained by the solvent-borne stain without compromising the performance of the complete system in terms of appearance.

Table 7. Color Variation (b* and ΔE) after Hot and Cold Check Test (KCMA/ANSI A161.1 2000), and Waller-Duncan Grouping

System	ΔB	Waller-Duncan grouping		System	ΔE	Waller-Duncan grouping
3	1.41	A		2	4.27	A
4	1.47	A		4	2.16	B
1	1.83	A	B	3	1.44	B
2	2.53		B	1	1.98	B

CONCLUSIONS

1. The furniture and kitchen cabinet industries are challenged to adopt low VOC finishing systems. The solutions available include the use of hybrid systems combining solvent-borne and water-borne components. In this study, four finishing systems were benchmarked. These were: 1) a solvent borne stain with a solvent-borne sealer and a solvent-borne lacquer; 2) a water-borne stain with a solvent-borne sealer and a solvent-borne lacquer; 3) a solvent-borne stain with a water-borne sealer, a second water-borne sealer and water-borne lacquer; and 4) a solvent-borne stain with a waterborne sealer and a waterborne lacquer.

2. Systems 3 and 4, which had the lowest solvent base components, yielded the lowest total VOC emission factor 3 days after manufacturing. After 21 days, Systems 1 and 2 had the lowest factors, low enough to meet major VOC regulations. Systems 3 and 4 also experienced a decrease in total VOC emission factors after 21 days but not as much as Systems 1 and 2. This is due to the significant amounts of high molecular weight solvent present in the water-borne components used in the formulation.

3. As the industry shifts from solvent-borne to water-borne components in its finishing systems, consumers expect not only a lower total VOC emission factor, but also good coating adhesion and appearance. Adhesion proved higher with the systems using a solvent-borne sealer and lacquer (Systems 1 and 2) than with those relying on a water-borne sealer and lacquer (Systems 3 and 4). On the other hand, the systems based on a solvent-borne sealer and lacquer (Systems 1 and 2) suffered a much greater degree of gloss loss after the hot box test than Systems 3 and 4. Color modification (b* and ΔE) was also slighter in the latter group.

4. The adoption of a hybrid strategy to reduce the total VOC emission factor is effective, but care must be taken with respect to the high molecular weight solvents associated with water-borne systems. As adhesion to wood may be negatively affected, wood surface preparation requires extra care to compensate. According to the hot box and hot and cold check tests, appearance may be more stable with the hybrid systems than with solvent-borne systems.

ACKNOWLEDGMENTS

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