REVIEW OF UNITED STATES AND INTERNATIONAL FORMALDEHYDE EMISSION REGULATIONS FOR INTERIOR WOOD COMPOSITE PANELS

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Abstract. This article compares and contrasts formaldehyde emission regulations for interior wood composite panels in the US, the European Union, Japan, and China. Historical context, product-specific emission limits, test methods, and product certification requirements are detailed for each emission standard. In particular, the recently enacted California Air Resources Board (CARB) formaldehyde regulation is compared with established international formaldehyde regulations and differences in four key areas, emission limits, documentation, deconstructive testing, and enforcement, are highlighted. Implications of CARB and US Environmental Protection Agency regulatory actions are discussed, and future work is suggested in the rapidly evolving and highly debated arena of formaldehyde emission policy.

Keywords: Formaldehyde emissions, wood composites, CARB regulation, indoor air quality.

INTRODUCTION

Exposure to formaldehyde in indoor environments gained attention as a public health concern in the early 1980s, mainly because of problems with mobile homes (Groah et al 1985). After Hurricane Katrina struck the gulf coast, formaldehyde garnered national attention as residents of government-provided trailers reported adverse health effects stemming from formaldehyde exposure. Symptoms included headaches, runny noses, chronic respiratory problems, and nose bleeds (Brunker 2006). Several governmental organizations subsequently investigated trailer air quality. Findings were the subject of congressional hearings held in 2007 and 2008. The Centers for Disease Control and Prevention (CDC) tested 519 occupied travel trailers, park models, and mobile homes supplied by the Federal Emergency Management Agency (FEMA) (CDC 2010) (Table 1). The average level of formaldehyde in all trailers was 77 parts per billion (ppb, mg/m^3) (CDC 2010). This is significantly higher than typical formaldehyde levels in US homes, which is 17-36 ppb (Hodgson et al 2000; Weisel et al 2005). However, it is lower than 100 ppb, which is the benchmark recognized by the CDC, Environmental Protection Agency (EPA), Consumer Products Safety Commission, the National

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Table 1. Formaldehyde emissions from Federal Emergency Management Agency-provided residences.[a]

Trailer type	Number tested	Mean formaldehyde emissions (mg/m^3)	95% CI about the mean (mg/m^3)	Range of emissions (mg/m^3)
Travel trailer	360	81	72-92	3-590
Park model	90	44	38-53	3-170
Mobile home	69	57	49-65	11-320

[a] Table data from Manufacturers (2008).

Institute of Occupational Safety and Health, and the World Health Organization; at this level, acute health effects begin to appear in healthy adults (US House, Committee on Oversight and Government Reform 2009). Table 1 shows the wide range of results (3-590 ppb, mg/m^3) found in the trailers tested (US House, Committee on Oversight and Government Reform 2009). The 95% confidence intervals indicate that the vast majority of all three types of FEMA-provided trailers were below the 100 ppb (0.1 ppm) threshold. However, the highest emission levels reported could have indeed caused significant health problems. The Occupational Safety and Health Administration (OSHA) requires medical monitoring of employees when their workplace exposure exceeds 500 ppb (OSHA 2010), and far more time is typically spent in a residence than in a workplace.

Maddelana et al (2008) suggested that extensive use and high surface loading of wood composites per unit area coupled with relatively low fresh air circulation within the trailers may have led to the elevated formaldehyde concentrations. For this reason, the Lawrence Berkeley National Laboratory (LBNL) conducted further research on trailer construction materials. On 8 May 2008, the CDC released preliminary test findings from the LBNL study, reporting that 44 of the 45 samples taken from the travel trailers were "at or well below the HUD standard for wood products" (US House, Committee on Oversight and Government Reform 2009).

The 9 July 2008 congressional hearing provided an interesting lens for this debate, because both sides of the issue were presented in detail (US House, Committee on Oversight and Government Reform 2009). On one side, both FEMA and trailer manufacturers were attacked for being aware of the formaldehyde problem and doing nothing. Detailed results of manufacturer-conducted tests were reported, revealing their awareness of exceedingly high formaldehyde levels in sealed unoccupied trailers. On the other side, manufacturers defended themselves according to the following tenets: (1) no national regulations or guidelines restricting formaldehyde levels in travel trailers and park models existed; (2) the recreational vehicle (RV) industry welcomed the development of such regulations; and (3) the RV Industry Association announced compulsory standards requiring all wood composite materials used after 1 July 2010 to comply with California Air Resources Board (CARB) emission limits (Manufacturers 2008). In summary, the testimony highlighted the need for more data on formaldehyde emissions from construction materials in housing, particularly at various temperature, humidity, and airflow conditions as well as the need for more widely applicable formaldehyde emission regulations.

The CARB emission limits became effective 1 January 2009, placing limits on formaldehyde emissions from wood composite panel products. Because California is a large and important market, CARB legislation is already driving major changes within the US and international wood composite panel industry as well as the resin industry that supplies it. Recently (7 July 2010), the President signed Senate Bill 1660, the Formaldehyde Standards for Composite Wood Products Act, which effectively extends CARB regulations to the entire US by adding Title VI to the Toxic Substances Control Act (S. 1660 2009). The bill directs the EPA to establish national protocols for implementation and compliance efforts by 1 January 2013 (S. 1660 2009).

This article reviews national and international formaldehyde emission regulations and the test methods used to quantify formaldehyde emissions from wood composite panel products. Additionally, the CARB regulation is reviewed in the context of existing international regulations.

Interior Wood Composite Panels

Interior wood composite panels (IWCP) such as hardwood plywood (HWPW), medium-density fiberboard (MDF), and particleboard (PB) are often used to construct furniture, cabinets, flooring, and wall panels. The IWCP industry is an important segment within the construction materials sector; 2007 North American production exceeded 14.3 million m^3, translating to US $4 billion (CPA 2008; HPVA 2008). PB is the most important IWCP product, representing approximately 58% and 45% of the production volume and value, respectively. MDF accounts for approximately 33% and 35% of production volume and value, respectively. HWPW accounts for only approximately 9% of production volume, however HWPW is a higher value product and represents about 20% of annual production value.

Formaldehyde Resins

Formaldehyde is a crosslinking agent in many IWCP binders (Maloney 1977; Sellers 2001). Urea–formaldehyde (UF) resins have traditionally been the predominant binder for PB, MDF, and HWPW; however, melamine–formaldehyde, melamine–urea–formaldehyde, phenol–formaldehyde (PF), phenol–melamine–urea formaldehyde, phenol–melamine formaldehyde, polymeric diphenylmethane diisocyanate, polyvinyl acetate, or soy-based resins can also be used depending on the desired panel properties (Maloney 1977; Vick 1999; Youngquist 1999; Sellers 2001; Kennedy 2005).

UF resins are popular because they are inexpensive, offer fast cure times, provide adequate bond strength for panels in low moisture applications, are colorless in cured form, and are easily adaptable to a variety of curing conditions (Pizzi 1983; Lorenz et al 1999). Disadvantages of traditional UF resins include their lack of moisture resistance and formaldehyde emissions (Pizzi 1983).

Mechanisms contributing to formaldehyde emissions from UF-bonded panels include unreacted "free formaldehyde" from the resin and hydrolysis of the partially cured and cured resin (Myers and Koutsky 1990; Yu and Crump 1999). The majority of formaldehyde emissions in IWCPs is attributed to free formaldehyde, and research shows these emissions typically decline exponentially until a steady state is reached (Yu and Crump 1999). As panels age, the bonded formaldehyde that is susceptible to hydrolysis makes a greater contribution to panel emissions (Yu and Crump 1999). Because formaldehyde can escape from the finished panels with time, IWCPs have been identified as a major source of airborne formaldehyde in homes (CARB 1991; EPA 2009).

US FORMALDEHYDE REGULATIONS

HUD

History. The first US legislation to limit IWCP formaldehyde emissions was enacted by the US Housing and Urban Development Agency (HUD) in 1985. This regulation was intended to limit indoor formaldehyde exposure in manufactured homes and until recently was the only national regulation restricting emissions from IWCPs in the US.

Emission limits. The product-specific emission limits and test methods associated with the HUD standard appear in Tables 2 and 3, respectively. Current HUD regulations do not cover MDF panels, although it is commonly used to construct cabinetry, molding, and millwork in manufactured housing (HUD 2006).

Certification. For a plant to attain or maintain certification, a government-approved third-party certification laboratory must witness or conduct large or small chamber testing on randomly selected panels at least quarterly and approve a written quality control (HUD 2006). If certified IWCPs are subsequently treated with

Table 2. Comparison of US and international emission limits.

	Product	Numerical value (mg/m^3)	Approximate US large-chamber value[a] (mg/m^3)
California Air Resources Board[b]			
Phase I	HWPW	0.08	0.08
	PB	0.18	0.18
	MDF	0.21	0.21
	Thin MDF[c]	0.21	0.21
Phase II	HWPW	0.05	0.05
	PB	0.09	0.09
	MDF	0.11	0.11
	Thin MDF	0.13	0.13
US (HUD)[d]			
	HWPW	0.2	0.2
	PB	0.3	0.3
Europe			
E1[e]	All	0.12	0.14 (for HWPW and PB)
E1[f]	PB, MDF, OSB	8 mg/100 g	0.10 (for MDF)
Japan[g]			
F***	All	0.5 mg/L	0.07
F****	All	0.3 mg/L	0.04
China			
E1[h]	PB, MDF, OSB	≤9 mg/100 g	0.11
E1[i]	HWPW	≤1.5 mg/L	0.21
Wood-based furniture[j]		≤1.5 mg/L	0.21

[a] Approximate ASTM E1333 values for Europe and Japan from CARB (2007a), Appendix H; values for China were estimated based on the equations for the European and Japanese test methods in CARB (2007a) and Risholm-Sundman et al (2007).
[b] Emission limits from large-chamber test (CARB 2007b).
[c] MDF with a maximum thickness of 8 mm (CARB 2007b).
[d] Emission limits from large-chamber test (HUD 2006).
[e] Value for EN 717-1 chamber test (BSI 2004).
[f] Value for EN 120 perforator test (BSI 2004).
[g] Emission limits from 24-h desiccator test (JSA 2003b).
[h] Value for perforator test (GAQSIQ 2001a).
[i] Value for desiccator test (9-11L) (GAQSIQ 2001a).
[j] Value for desiccator test (9-11L) (GAQSIQ 2001b).
HWPW, hardwood plywood; PB, particleboard; MDF, medium-density fiberboard; OSB, oriented strandboard.

paint, varnish, or any other substance containing formaldehyde, the certification becomes invalid, but the panels can be retested (HUD 2006).

Although the HUD standard only applies to a specific residential market (manufactured homes), the regulation established a baseline for IWCP formaldehyde emissions and encouraged many HWPW and PB manufacturers to modify their products to comply with the standard (CARB 2007a). The industry complied with voluntary product standards incorporating the HUD emission limits and test methods (CPA 1999, 2002; ASTM 2002; HPVA 2004) until the more stringent CARB rule emerged (Turner et al 1996). The American National Standards Institute requires certified third-party testing facilities to develop their own protocols for product testing frequency and quality control testing to ensure products meet emission limits (CPA 2010; HPVA 2010).

California Air Resources Board

History. On 12 March 1992, CARB identified formaldehyde as a toxic air contaminant with no safe exposure threshold level (CEPA 2008). During the initial evaluation of indoor formaldehyde exposure in California, the CARB found that IWCPs containing formaldehyde-based resins were a major source of formaldehyde exposure. On 18 April 2008, the airborne toxic control measure to control formaldehyde emissions from composite wood products was approved by the Office of Administrative Law, and emission standards were implemented on 1 January 2009 (CEPA 2008).

Emission limits. Emission reductions will occur in a two-phase process. The majority of phase I (P1) reductions became effective 1 January 2009, and the more restrictive phase II (P2) reductions take effect between 2010 and 2012 (CARB 2007b). Table 2 shows the CARB P1 and P2 emission limits.

The CARB regulation requires documentation throughout the value chain to ensure that finished goods sold in California contain CARB-compliant materials. Each panel or bundle must be clearly labeled with the manufacturer's name, lot or batch number, a marking to denote compliance with the applicable P1 or P2 emission standards, and the CARB-assigned number for the third-party certifier (CARB 2007b). Additionally, fabricators must label finished goods, and the bill of lading or invoice provided to distributors, importers, other fabricators, or

Table 3. Comparison of US and international emission test methods.

Purpose	Product	Test method	Chemistry
		California Air Resources Board (Phase I and II)	
Certification	All	Large/small chamber[a]	Chromatropic acid or DNPH[b]
Quality control	All	Small chamber or desiccator[c]	Chromatropic acid or DNPH
		US (HUD)	
Certification	All	Large chamber[d]	Chromatropic acid
Quality control	All	Not specified	Not applicable
		Europe (E1)	
Certification	All	Large chamber[e,f]	Acetylacetone
Quality control	PB, OSB, MDF	Perforator[g]	Acetylacetone
Quality control	HWPW and finished panels	Gas analysis[h]	Acetylacetone
		Japan	
Certification	All	Chamber or desiccator[i]	DNPH/acetylacetone[j]
Quality control	All	Chamber or desiccator	DNPH/acetylacetone
		China (E1 and E2)	
Certification	MDF, PB, OSB	Perforator[k]	Acetylacetone
Certification	Plywood	9-11L desiccator	Acetylacetone
Certification	Finished panels	Chamber or 40-L desiccator	Acetylacetone
Quality control	All	Not specified	Not applicable

[a] ASTM E 1333 large chamber (ASTM 2002) or ASTM D 6007 small chamber (ASTM 2006b).
[b] DNPH-dinitrophenylhydrazine method (ASTM 2003).
[c] ASTM D 6007 small chamber (ASTM 2006b) or ASTM D 5582 desiccator method (ASTM 2006a). The Japanese desiccator method (JIS A 1460), the European gas analysis method (EN 717-2), the dynamic microchamber, and European perforator method (EN 120) (only for PB, MDF, and thin MDF) are also CARB-approved quality control test methods.
[d] ASTM E 1333 large-chamber method (ASTM 2002).
[e] EN 717-1 large-chamber method (CEN 1997a).
[f] Quality control methods (perforator and gas analysis) may be used for certification testing (BSI 2004).
[g] EN 120 perforator method (CEN 1997b).
[h] EN 717-2 gas analysis method (CEN 1994).
[i] JIS A 1901 chamber method (JSA 2003a) or JIS A 1460 desiccator method (JSA 2001).
[j] Chamber method specifies DNPH method and desiccator method specifies acetylacetone method.
[k] GB/T 17657-1999 perforator method (GAQSIQ 1999).
PB, particleboard; OSB, oriented strandboard; MDF, medium-density fiberboard; HWPW, hardwood plywood.

retailers must indicate that the goods were made with compliant materials (CARB 2007b).

Certification. In-house quality control (QC) testing, third-party certifier inspections, and CARB inspections provide product certification. The majority of the testing burden falls on the IWCP manufacturers. Manufacturers are required to either establish an in-house formaldehyde testing laboratory that is certified by a third-party organization or contract QC testing to a third-party certified facility (CARB 2007b). Typical large- and small-chamber third-party testing facilities are depicted in Figs 1 and 2, respectively.

In addition to small-scale QC testing, the third-party certifier randomly selects samples of each product type and conducts a primary (large chamber) or secondary (small chamber or desiccator) test to determine compliance (CARB 2007b). The CARB-approved test methods and chemical analysis methods for QC and product certification testing are outlined in Table 3.

Fabricators who produce laminated products do not need to comply with third-party certification, although fabricators may use resins containing formaldehyde to apply surface treatments or assemble products (CARB 2007b). This exemption has sparked controversy within the IWCP industry because fabricators often apply veneers to the face and back of plywood, PB, or MDF cores—effectively forming a HWPW product—which they do not certify with a third party. Although fabricators do not need to comply with

Figure 1. Typical large-chamber testing facility at a California Air Resources Board-approved third-party certifier (top photo: exterior of large chambers with air sampling apparatus shown at the Composite Panel Association testing facility in Leesburg, VA; bottom photo: interior of large chamber with samples loaded for testing).

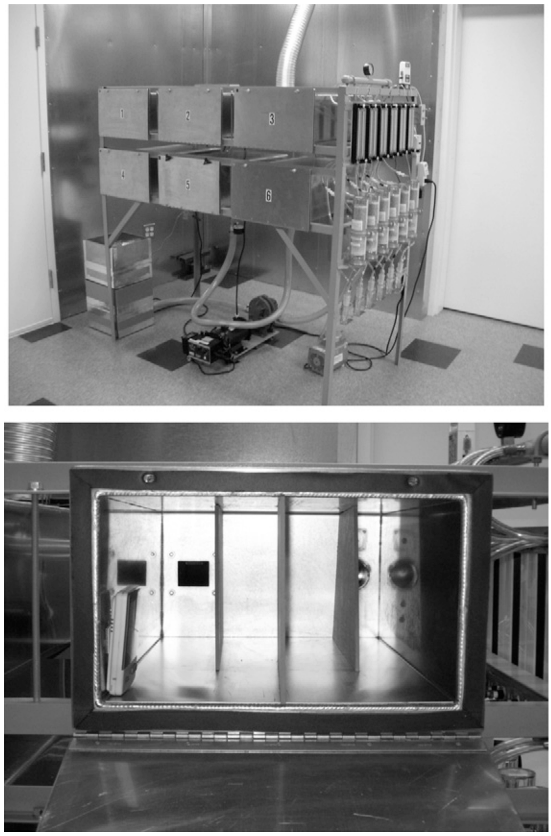

Figure 2. Typical small-chamber testing facility at a California Air Resources Board-approved third-party certifier (top photo: bank of six small chambers at the Composite Panel Association testing facility in Leesburg, VA; bottom photo: interior of small chamber with samples loaded for testing).

the manufacturer requirements in the regulation, they are subject to periodic inspection by CARB personnel to audit records and secure samples for testing, including samples from finished goods (CARB 2007b). Further discussion of CARB regulations is provided in the Comparison of Regulations section.

INTERNATIONAL FORMALDEHYDE REGULATIONS

European Union

History. In 1988, the European Parliament enacted the Construction Products Directive, which requires construction products circulated in European Union (EU) member countries to meet an essential requirement for "Hygiene, Health and the Environment" as defined in EU or national regulations (ECC 2009a). This essential requirement includes provisions that limit common indoor air pollutants such as formaldehyde (ECC 2009b). Emission limits for wood composite panel products were developed in the European Standardization Organization (CEN) to ensure compliance with existing regulations in Austria, Germany, Denmark, and Sweden (Fuchs 2009).

Emission limits. The European system places panel products into two classes, E1 or E2, based on formaldehyde emissions (BSI 2004). The emission limits for the more stringent E1 class appear in Table 2. Although emission limits are not product-specific, different QC test methods are used for some products (Table 3). Some EU member countries choose to enact more stringent emission standards such as only allowing E1 class materials (BSI 2004).

Certification. To certify products, government-approved, third-party certification bodies develop specific product testing arrangements in cooperation with manufacturers (Fuchs 2009). Generally, manufacturers are required to conduct QC testing once per 24-h production period (once per week for plywood and solid wood panels) using the methods outlined in Table 3 (BSI 2004).

Japan

History. In 2003, a revised version of the Japanese building standard law (BSL) took effect, adding restrictions on building materials containing chlorpyrifos (a pesticide) and formaldehyde (BCJ 2009). The regulation places restrictions on the area of formaldehyde-emitting building materials that can be used as interior finishing materials (BCJ 2009). Use restrictions are based on the emission class of the panel product, the type of habitable room, and the ventilation frequency of the room (BCJ 2009). In addition to restrictions on use in habitable rooms, the regulations also place restrictions on formaldehyde emissions from building materials used in ceiling cavities, attics, crawl spaces, and storerooms (BCJ 2009). The emission limits for the two most stringent classes, F**** and F***, appear in Table 2.

Emission limits. The BSL regulations do not apply directly to finished products; however, applicable finished products intended for use in habitable rooms must be made with certified materials (Matsuyama 2009). Building materials made of more than one formaldehyde-emitting material are placed into the lowest class (MLIT 2003). Likewise, cabinets and doors or windows assembled at factories using multiple building materials are classified according to the materials they contain (MLIT 2003). Testing is conducted on the finished panel product, making it possible to use high-emitting material in the core of a product and then apply decorative surface treatments, which sufficiently seal the surface to restrict formaldehyde emissions (Matsuyama 2009). This approach can effectively reduce panel emissions by as much as 95% (Groah et al 1992; CPA 2003; Barry and Corneau 2006).

Certification. Products must be certified by third-party testing facilities, and both primary and secondary products must carry labels identifying the emission class (Mazikins 2003; MLIT 2003). The manufacturer should conduct QC testing to ensure compliance with the formaldehyde emission criteria; however, in practice, this testing is often conducted by the grading agencies that are Japanese Standards Association-accredited (Matsuyama 2009). Certification and QC test methods are outlined in Table 3.

China

History. In 2001, the Standardization Administration and the General Administration for Quality Supervision, Inspection, and Quarantine of the People's Republic of China enacted comprehensive national emission standards limiting harmful substances from indoor decorating and refurbishing materials. These regulations included ten national standards that placed restrictions on wood-based panels, wood-based furniture, adhesives, and solvent coatings for wood products.

Emission limits. The Chinese standards and test methods are essentially adaptations of European and Japanese regulations. Both structural and nonstructural panel products are included. Emission limits are product-specific and place limitations on end use (Table 2). E2 class materials can be used in indoor applications only after decorative surface treatments are applied (GAQSIQ 2001a). In addition to the panel standard, the Chinese also have a standard that places restrictions on formaldehyde emissions from finished furniture (GAQSIQ 2001b). Emission limits and the relevant test methods appear in Tables 2 and 3, respectively. This standard also restricts the amount of four heavy metals (lead, cadmium, chromium, and mercury) in the surface layer of furniture (GAQSIQ 2001b).

Certification. Product certification is achieved through voluntary application to third-party, independent testing centers. These centers are approved by the Certification and Accreditation Administration of China. Government-accredited certification centers include the China Quality Certification Center (CQC), China Environmental United Certification Center, and China Standard Certification Center (CSC). Each certification center establishes their own technical requirements, including test methods and emission limits, which are based on the national standards outlined in Table 3 (CQC 2003; CSC 2004).

COMPARISON OF REGULATIONS

Emission limits. The emission limits in the CARB regulation are not radically different from the equivalent international standards. CARB P2 emission limits are lower than European and Chinese E1 limits, approximately equivalent to the Japanese F*** limits, and higher than the Japanese F**** limits (Table 2). However, the CARB emission limits represent "ceilings" that cannot be exceeded, whereas the Japanese limits in Table 2 are average values and permit some panels to exceed the mean, up to a maximum allowable limit, as long as the mean value is attained during a normal production period (JSA 2003b). To meet CARB standards, manufacturers aim for emission levels below the ceilings because of variability in panel emissions.

Comparisons among different standards and regulations are difficult. The various test methods cause different emission characteristics. Just a few of the differences among methods include panel equilibration before testing, edge sealing, and temperature, RH, and airflow during testing.

Documentation. A major difference between CARB and other IWCP formaldehyde emission regulations is the CARB chain-of-custody requirements. Arguably, this makes CARB the toughest standard in the world (Bradfield 2008). Fabricators must take "reasonable prudent precautions" to purchase IWCPs and IWCP-containing products that meet the applicable P1 or P2 standards (CARB 2007b). Fabricators must also keep documents showing the date of purchase and supplier of IWCPs and/or finished goods containing IWCPs plus they must document the precautions taken to ensure all components in finished goods comply with the applicable CARB standards (CARB 2007b). Records must be maintained for at least 2 yr (CARB 2007b). Distributors and retailers must maintain similar records to ensure that finished goods sold in California are compliant and that raw materials in the finished product can be traced through the value chain to the IWCP manufacturer (CARB 2007b).

Deconstructive testing. Also unique to the CARB regulation is its provision for deconstructive testing. This is an attempt to verify that compliant panels were used to construct finished products; in other words, this will provide an avenue to catch falsely certified products. CARB personnel are likely to use a secondary test method such as the small chamber method (ASTM 2006b) to test pieces of HWPW, PB, and MDF that are removed from finished goods (CARB 2007b). Currently, CARB personnel, who are reportedly in consultation with both industry and academic professionals, are developing a detailed protocol for the isolation of samples (Bradfield 2008). Under the recently signed legislation, the EPA will assume these responsibilities for the nationwide regulation.

Several potential deconstructive testing approaches have been conceptualized. One method uses either abrasive sanding or planing to remove decorative surface treatments so that underlying panels may be tested (Bradfield 2008). However, there are concerns about this approach. A layer of minimum permeability exists just below the surface of PB, and this high-density region provides resistance to formaldehyde emissions. This layer may only be 1 mm thick, hence easily removed by sanding or planning, allowing formaldehyde emission values to exceed those noted in the panel production facility (Christensen et al 1987). Philosophically, some object to this approach because it targets emissions from panel components that may be sealed within finished products. An argument can clearly be made that the total emissions from an intact finished product should be the paramount concern. As previously noted, materials sealed within an assembly do not have the same emission characteristics as those exposed to surfaces (Groah et al 1992; CPA 2003; Barry and Corneau 2006).

Enforcement. Enforcement varies widely among the standards, making compliance more important in some areas. The US is an extremely litigious environment compared with China, Japan, or the EU. US firms who fail to comply with regulations are often targets for large class-action lawsuits. Therefore, companies operating in the US will probably follow strict QC practices with frequent product testing to provide a measure of protection from litigation. Companies operating in less litigious countries may conduct minimal testing to comply with government regulations.

Summary. The CARB regulation has renewed interest in the formaldehyde emission arena and created research opportunities. For example, little is known about how various deconstructive testing methods will affect emission test results. Additionally, some uncertainty remains when comparing international emission limits and there is a need for better data comparing US test methods with the various international test methods so that IWCP producers can better navigate international emission standards. These will be challenges the EPA will encounter as it establishes national protocols for implementation and compliance of Senate Bill 1660, which effectively nationalizes CARB emission limits.

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REFERENCES

ASTM (2002) Standard test method for determining formaldehyde concentrations in air and emission rates from wood products using a large chamber. Method E 1333-96. American Society for Testing and Materials, West Conshohocken, PA. 12 pp.

ASTM (2003) Standard test method for determination of formaldehyde and other carbonyl compounds in air: Active sampler methodology. Method D 5197-03. American Society for Testing and Materials, West Conshohocken, PA. 15 pp.

ASTM (2006a) Standard test method for determining formaldehyde levels from wood products using a desiccator. Method D 5582-00. American Society for Testing and Materials, West Conshohocken, PA. 7 pp.

ASTM (2006b) Standard test method for determining formaldehyde concentration in air from wood products using a small-scale chamber. Method D 6007-02. American Society for Testing and Materials, West Conshohocken, PA. 8 pp.

Barry A, Corneau D (2006) Effectiveness of barriers to minimize VOC emissions including formaldehyde. Forest Prod J 56(9):38-42.

BCJ (2009) Introduction: Overview of countermeasures regarding sick house issues under the amended building standard law. The Building Center of Japan, Tokyo. http://www.bcj.or.jp/en/services/evaluation/issue/issue02.html (25 January 2009).

Bradfield J (2008) California's 2009 formaldehyde regulations: What does the new CARB rule mean for wood products manufacturers? Forest Products Society Webinar. 16 December 2008. Forest Products Society, Madison, WI.

Brunker M (2006) Are FEMA trailers 'toxic tin cans'? MSNBC. http://www.msnbc.msn.com/id/14011193/ (23 January 2009).

BSI (2004) Wood-based panels for use in construction—Characteristics, evaluation of conformity and marking. BS EN 13986: 2004. British Standards Institution, London, UK. 60 pp.

CARB (1991) Formaldehyde in the home. Indoor air quality guideline. California Air Resources Board, Research Division, Sacramento, CA. 5 pp.

CARB (2007a) Proposed airborne toxic control measure to reduce formaldehyde emissions from composite wood products. California Air Resources Board, Stationary Sources Division, Sacramento, CA. 225 pp.

CARB (2007b) Airborne toxic control measure to reduce formaldehyde emissions from composite wood products. California Air Resources Board, Stationary Sources Division, Sacramento, CA. 59 pp.

CDC (2010) Formaldehyde—Related health concerns. Centers for Disease Control and Prevention. http://www.cdc.gov/Features/FEMAtrailers/ (12 January 2010).

CEN (1994) Wood-based panels- Determination of formaldehyde release—Part 2: Formaldehyde release by the gas analysis method. EN 717-2. Comitè Europèen De Normalisation. Central Secretariat, Brussels, Belgium. 22 pp.

CEN (1997a) Wood-based panels—Determination of formaldehyde release—Part 1: Formaldehyde emission by the chamber method. EN 717-1. Comitè Europèen De Normalisation. Central Secretariat, Brussels, Belgium. 36 pp.

CEN (1997b) Wood-based panels—Determination of formaldehyde content—Extraction method called the perforator method. EN 120. Comitè Europèen De Normalisation. Central Secretariat, Brussels, Belgium. 17 pp.

CEPA (2008) Composite wood ATCM. California Environmental Protection Agency. http://www.arb.ca.gov/toxics/compwood/compwood.htm (12 September 2008).

Christensen RL, Anderson WH, Stewart SD (1987) The influence of particleboard structure on formaldehyde emissions. Pages 117-130 *in* TM Maloney, ed. Proc 21st Int. Particleboard/Composite Materials Symp. Washington State University, Pullman, WA.

CPA (1999) American National Standard: Particleboard. ANSI A208.1-1999. Composite Panel Association, Leesburg, VA. 11 pp.

CPA (2002) American National Standard: Medium density fiberboard (MDF) for interior applications. ANSI A208.2-2002. Composite Panel Association, Leesburg, VA. 11 pp.

CPA (2003) VOC emission barrier effects of laminates, overlays and coatings for particleboard, medium density fiberboard (MDF) and hardboard. Technical Bulletin. Composite Panel Association, Leesburg, VA. 8 pp.

CPA (2008) 2007 North American shipments report: Particleboard, medium density fiberboard, hardboard. Composite Panel Association, Leesburg, VA. 21 pp.

CPA (2010) Personal communication with the Composite Panel Association. Leesburg, VA (20 January 2010).

CQC (2003) Voluntary product certifiable special requirement for indoor decorating and refurbishing materials—Wood-based panels and finishing products. CQC/RY507-2003. China Quality Certification Center, Beijing, China. 9 pp.

CSC (2004) Wood-based panels and finishing products. CSC/G2201-2004. China Standard Certification Center, Beijing, China. 1 p.

ECC (2009a) The construction products directive (Council Directive 89/106/EEC). European Communities Commission, Enterprise and Industry. http://ec.europa.eu/enterprise/construction/internal/cpd/cpd.htm#1 (23 March 2009).

ECC (2009b) Basis for verification of the satisfaction of the essential requirement 'Hygiene, health and the environment.' European Communities Commission, Enterprise and Industry. http://ec.europa.eu/enterprise/construction/internal/intdoc/id3/basisid3.htm (23 March 2009).

EPA (2009) An introduction to indoor air quality—Formaldehyde. Environmental Protection Agency. http://www.epa.gov/iaq/formalde.html (23 March 2009).

Fuchs M (2009) Directorate-General Enterprise and Industry. European Commission. Brussels, Belgium, Belgium. Personal Communication with T Ruffing on 30 April 2009.

GAQSIQ (1999) Test methods of evaluating the properties of wood-based panels and surface decorated wood-based panels. GB/T 17657-1999. General Administration Quality Supervision, Inspection and Quarantine, Peoples Republic of China, Beijing, China. 59 pp.

GAQSIQ (2001a) Indoor decorating and refurbishing materials—Limit of formaldehyde emission of wood-based panels and finishing products. GB 18580-2001. General Administration Quality Supervision, Inspection and Quarantine, Peoples Republic of China, Beijing, China. 7 pp.

GAQSIQ (2001b) Indoor decorating and refurbishing materials—Limit of harmful substances of wood-based furniture. GB 18584-2001. General Administration Quality Supervision, Inspection and Quarantine, Peoples Republic of China, Beijing, China. 7 pp.

Groah WJ, Gramp GD, Garrison SB, Walcott RJ (1985) Factors that influence formaldehyde air levels in mobile homes. Forest Prod J 35(2):11-18.

Groah WJ, Gramp GD, Rudzinski RJ (1992) The effect of surface ply thickness on formaldehyde emissions from a diffuse porous hardwood. Forest Prod J 42(7/8):54-56.

Hodgson AT, Rudd AF, Beal D, Chandra S (2000) Volatile organic compound concentrations and emission rates in new manufactured and site-built houses. Indoor Air 10:178-192.

HPVA (2004) American national standard for hardwood and decorative plywood. ANSI/HPVA HP-1-2004. Hardwood Plywood and Veneer Association, Reston, VA. 35 pp.

HPVA (2008) Hardwood stock panels: Annual statistical report for calendar year 2007. Hardwood Plywood and Veneer Association, Reston, VA. 92 pp.

HPVA (2010) Personal communication with the Hardwood Plywood & Veneer Association, Reston, VA (19 January 2010).

HUD (2006) Manufactured home construction and safety standards. 24 CFR Part 3280. Department of Housing and Urban Development, Office of the Assistant Secretary for Housing—Federal Housing Commissioner, Washington, DC. pp. 138-139, 148.

JSA (2001) Building boards determination of formaldehyde emission-desiccator method. Method JIS A 1460. Japanese Standards Association, Tokyo, Japan. 11 pp.

JSA (2003a) Determination of the emission of volatile organic compounds and aldehydes for building products—Small chamber method. Method JIS A 1901. Japanese Standards Association, Tokyo, Japan. 39 pp.

JSA (2003b) Fiberboards. Standard JIS A 5905. Japanese Standards Association, Tokyo, Japan. 36 pp.

Kennedy HJ (2005) The North American wood adhesives market. Pages 33-38 *in* CR Frihart, ed. Proc Wood Adhesives, 2-4 November 2005, San Diego, CA. Forest Prod Soc, Madison, WI.

Lorenz LF, Conner AH, Christiansen AW (1999) The effect of soy protein additions on the reactivity and formaldehyde emissions of urea–formaldehyde adhesive resins. Forest Prod J 49(3):73-78.

Maddalena R, Russell M, Sullivan DP, Apte MG (2008) Aldehyde and other volatile organic chemical emissions in four FEMA temporary housing units—Final report. Ernest Orlando Lawrence Berkeley National Laboratory, Environmental Energy Technologies Division. 61 pp.

Maloney TM (1977) Modern particleboard and dry-process fiberboard manufacturing. Miller Freeman, San Francisco, CA. 672 pp.

Manufacturers (2008) Manufacturers of FEMA trailers and elevated formaldehyde levels. Hearing before the committee on oversight and governmental reform. House of Representatives, One Hundred Tenth Congress. 9 July 2008. US Government Printing Office. Washington, DC.

Matsuyama E (2009) Japan Director. American Forest and Paper Association (AF&PA). Tokyo, Japan. Personal communication with T Ruffing on 2 April 2009.

Mazikins P (2003) Japan: New regulatory challenges. 20th International Forest Products Markets Conference. 16-17 October 2003. Center for International Trade in Forest Products, Seattle, WA.

MLIT (2003) Method of examination for formaldehyde-emitting building materials. Housing Bureau, Ministry of Land, Infrastructure and Transport, Tokyo, Japan. 14 pp.

Myers GE, Koutsky JA (1990) Formaldehyde liberation and cure behavior of urea–formaldehyde resins. Holzforschung 44(2):117-126.

OSHA (2010) Enforcement procedure for occupational exposure to formaldehyde. CPL 02-02-052. Occupational Health and Safety Administration, US Department of Labor. http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=DIRECTIVES&p_id=1566 (1 April 2010).

Pizzi A (1983) Aminoresin wood adhesives. Pages 59-104 *in* A Pizzi, ed. Wood adhesives, chemistry and technology. Marcel Dekker, New York, NY.

Risholm-Sundman M, Larsen A, Vestin E, Weibull A (2007) Formaldehyde emission—Comparison of different standard methods. Atmos Environ 41(15):3193-3202.

S. 1660 (2009) S. 1660–111th Congress: Formaldehyde standards for composite wood products act. *In:* GovTrack.us (database of federal legislation). http://www.govtrack.us/congress/bill.xpd?bill=s111-1660 (22 July 2010).

Sellers T Jr (2001) Wood adhesives innovations and applications in North America. Forest Prod J 51(6): 12-22.

Turner S, Martin C, Hetes R, Northeim C (1996) Sources and factors affecting indoor emissions from engineered wood products: Summary and evaluation of current literature. Project Summary No. EPA/600/SR-96/067. USEPA, National Risk Management Research Laboratory, Research Triangle Park, NC. 4 pp.

US House, Committee on Oversight and Government Reform (2009) Manufacturers of FEMA trailers and elevated formaldehyde levels, Hearing, 9 July 2008 (Serial No. 110-132). Government Printing Office, Washington, DC.

Vick CB (1999) Adhesive bonding of wood materials. Chapter 9 *in* Wood handbook: Wood as an engineering material. Gen Tech Rep FPL-GTR-113. USDA For Serv Forest Prod Lab, Madison, WI. 463 pp.

Weisel CP, Zhang J, Turpin BJ, Morandi MT, Colome S, Stock TH, Spektor DM (2005) Relationship of indoor, outdoor, and personal air (RIOPA). Part I. Collection methods and descriptive analyses. Research Report (Health Effects Institute) (130 part 1). 144 pp.

Youngquist CB (1999) Wood-based composites and panel products. Chapter 10 *in* Wood handbook: Wood as an engineering material. Gen Tech Rep FPL-GTR-113. USDA For Serv Forest Prod Lab, Madison, WI. 463 pp.

Yu CWF, Crump DR (1999) Testing for formaldehyde emission from wood-based products—A review. Indoor Built Environ 8:280-286.