



**PROPOSED AIRBORNE TOXIC CONTROL MEASURE TO REDUCE  
FORMALDEHYDE EMISSIONS FROM COMPOSITE WOOD PRODUCTS**



**Stationary Source Division  
Air Quality Measures Branch**

**Release Date: March 9, 2007**

**To Be Considered by the Board: April 26, 2007**

State of California  
AIR RESOURCES BOARD

**STAFF REPORT: INITIAL STATEMENT OF REASONS  
FOR PROPOSED RULEMAKING**

**Public Hearing to Consider**

**ADOPTION OF THE PROPOSED AIRBORNE TOXIC CONTROL MEASURE  
TO REDUCE FORMALDEHYDE EMISSIONS FROM COMPOSITE WOOD  
PRODUCTS**

To be considered by the Air Resources Board on April 26, 2007, at:

California Environmental Protection Agency  
Headquarters Building  
1001 "I" Street  
Sacramento, California

Stationary Source Division:  
Robert Fletcher, P.E., Chief, Stationary Source Division  
Robert D. Barham, Ph.D., Assistant Division Chief, Stationary Source Division  
Janette Brooks, Chief, Air Quality Measures Branch  
Jim Aguila, Manager, Substance Evaluation Section

This report has been prepared by the staff of the Air Resources Board. Publication does not signify that the contents reflect the views and policies of the Air Resources Board, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

# **Acknowledgements**

## **Contributing Authors**

Brent Takemoto, Ph.D. (Lead)  
James Stebbins  
Lynn Baker  
Angela Csondes  
Susie Chung  
Melanie Marty, Ph.D.  
Andy Salmon, Ph.D.  
Robert Blaisdell, Ph.D.  
Reza Mahdavi, Ph.D.  
Peggy Jenkins  
Linying Li  
Webster Tasat  
Andy Delao  
Elizabeth Miller  
Darrell Hawkins  
Michael Poore  
Russell Grace  
Jose Saldana

## **Legal Counsel**

Robert Jenne, Esq., Office of Legal Affairs

---

**We also wish to acknowledge the assistance and cooperation we received from many individuals and organizations. In particular, we would like to thank:**

Composite Panel Association, Hardwood Plywood and Veneer Association, American Home Furnishers Association, Kitchen Cabinet Manufacturers Association, Woodwork Institute, Formaldehyde-Free Coalition, California Wood Industries Coalition, Columbia Forest Products, Sierra Pine, Professional Service Industries, Inc., General Veneer, G.L. Veneer, Georgia Pacific, Hexion,

# TABLE OF CONTENTS

<b>Executive Summary</b>	<b>ES-1</b>
I. Introduction .....	1
A. Regulatory Authority.....	2
B. Formaldehyde in California .....	3
C. Need for Reducing Formaldehyde Emissions from Composite Wood Products.....	5
D. Regulations Applicable to Formaldehyde.....	6
E. Indoor Air Quality .....	7
F. References.....	7
II. Public Outreach.....	9
A. Outreach Efforts .....	9
B. Public Involvement.....	9
C. Survey of Products Manufactured in 2002 .....	11
D. References.....	12
III. Need for Regulation of Formaldehyde (HCHO) .....	13
A. Health Effects of Formaldehyde .....	13
B. Physical and Chemical Properties.....	13
C. Sources and Emissions of Formaldehyde.....	14
D. Emissions from Composite Wood Products .....	19
E. Natural Occurrences .....	20
F. Measured Formaldehyde Concentrations .....	21
G. Modeled Formaldehyde Concentrations .....	32
H. Atmospheric Persistence.....	33
I. Risk Characterization .....	33
J. References.....	34
IV. Manufacturing of Composite Wood Products.....	42
A. Background.....	42
B. Composite Wood Product Manufacturing Plants.....	42

C.	Resins Currently Used in Composite Wood Products .....	45
D.	References.....	59
V.	Assessment of Best Available Control Technology (BACT) .....	63
A.	Introduction .....	63
B.	Product Descriptions and Survey Results .....	70
C.	Present-day Resin Technologies .....	75
D.	Candidate Low-formaldehyde Resin Systems.....	83
E.	Technical Basis for the Proposed Emission Standards.....	101
F.	References.....	108
VI.	Proposed Airborne Toxic Control Measure (ATCM).....	116
A.	Summary of the Proposed Airborne Toxic Control Measure.....	116
B.	Alternatives to the Proposed Airborne Toxic Control Measure.....	128
C.	Conclusion .....	129
VII.	Health Impacts of the Proposed Airborne Toxic Control Measure.....	130
A.	Overview of the Health Risk Assessment .....	130
B.	Total Daily Formaldehyde Exposure as the Basis for Risk Assessment	132
C.	Factors that Affect the Outcome of a Health Risk Assessment.....	155
D.	Summary of Potential Health Impacts .....	155
E.	Multi-pathway Health Risk Assessment .....	157
F.	Statewide Emission and Risk Reduction Benefits .....	157
G.	Potential Adverse Health Effects from Replacement Compounds .....	159
H.	Workplace Exposure .....	160
I.	References.....	161
VIII.	Economic Impacts of the Proposed Airborne Toxic Control Measure ....	178
A.	Background.....	178
B.	Cost of Compliance.....	189
C.	Cost to the Composite Wood Manufacturing Industry .....	205
D.	Distributor and Importer Costs .....	209
E.	Fabricator Costs.....	211
F.	Retailer Costs.....	213
G.	Consumer Costs .....	213

H.	Impacts to Small Business .....	216
I.	References.....	216
IX.	Environmental Impacts of the Proposed Airborne Toxic Control Measure .....	221
A.	Legal Requirements .....	221
B.	Analysis of Reasonably Foreseeable Environmental Impacts.....	221
C.	Reasonably Foreseeable Feasible Mitigation Measures .....	224
D.	Reasonably Foreseeable Alternative Means of Compliance .....	224
E.	Community Health and Environmental Justice.....	224
F.	References.....	224

## List of Tables

Table ES-1.	Proposed Phase 1 and Phase 2 Emission Standards .....	3
Table ES-2.	Estimated Reductions in Cancer Risk After Phase 1 and Phase 2.....	6
Table ES-3.	Total Estimated Cost to the Industry in 2002 .....	9
Table II-1.	Selected ATCM-related Outreach Efforts .....	9
Table III-1.	Physical and Chemical Properties of Formaldehyde .....	14
Table III-2.	Product Distribution for Formaldehyde in the U.S. (2003).....	15
Table III-3.	Formaldehyde – 2005 Statewide Emission Inventory .....	16
Table III-4.	Emission Rates of Selected Indoor Sources of Formaldehyde ( $\mu\text{g}/\text{m}^2/\text{hr}$ ).....	18
Table III-5.	Statewide Annual Average Formaldehyde Concentrations ( $\mu\text{g}/\text{m}^3$ ): 1996-2005 .....	22
Table III-6.	Summary of Ambient Formaldehyde Concentrations ( $\mu\text{g}/\text{m}^3$ ): 1 January 2005 through 30 April 2006.....	25
Table III-7.	Formaldehyde Emissions in the Top Ten California Counties ....	26
Table III-8.	Measured Indoor Formaldehyde Concentrations ( $\mu\text{g}/\text{m}^3$ ) .....	27
Table IV-1.	Advantages and Disadvantages of Urea-formaldehyde Resins.....	47
Table IV-2.	Characteristics of Urea-formaldehyde (UF) Resins .....	49
Table IV-3.	Characteristics of Phenol-formaldehyde (PF) Resins .....	51
Table IV-4.	Summary of Melamine-based Resin Properties and Uses.....	53
Table IV-5.	Advantages and Disadvantages of Polydiphenylmethane Diisocyanate (pMDI) Resins .....	54
Table IV-6.	Characteristics of MDI Resins.....	55
Table IV-7.	Characteristics of Polyvinyl Acetate (PVA) Resins .....	57
Table V-1.	List of Researchers, Manufacturers, and Academia Contacted .....	65
Table V-2.	Japanese Building Standard Law Classifications for Building Material Formaldehyde (HCHO) Emissions .....	68
Table V-3.	Formaldehyde (HCHO) Emission Standards for Composite Wood Products in the U.S., Europe, and Japan .....	70
Table V-4.	Measured or Estimated ASTM E1333 Average Data for Hardwood Plywood-Veneer Core from Selected U.S. Manufacturers.....	72

Table V-5.	Measured or Estimated ASTM E1333 Data for Hardwood Plywood-Composite Core from Selected U.S. Manufacturers ....	73
Table V-6.	Effect of Melamine Acetate (Mac) on Plywood Tensile Strength .....	76
Table V-7.	Comparison of Strength and HCHO Emission Properties of Particleboard Made with Two Melamine-formaldehyde (MF) Resins.....	78
Table V-8.	Selected Measures of Tensile Strength (N/mm <sup>2</sup> ) in Plywood Made with Urea-formaldehyde (UF) and UF-Methylene Diisocyanate (UF-MDI) Hybrid Resins.....	80
Table V-9.	Effect of MDI and/or Urea Additions on Selected Resin and Panel Properties in Particleboard Made with Phenol-urea-formaldehyde (PUF) Resins.....	81
Table V-10.	Dry and Wet Internal Bond (IB) Strength and Density in Particleboard Made Phenol-melamine-urea-formaldehyde (PMUF)-MDI Resins .....	82
Table V-11.	Soy-based Adhesives: Problems and Solutions .....	86
Table V-12.	Physical Properties of Phenol-formaldehyde (PF) and Soy-PF Resins.....	87
Table V-13.	Effect of Tris(hydroxymethyl)nitromethane (TN) Addition on the Breaking Loads and Formaldehyde Contents of Plywood Made with Quebracho Tannin Resin .....	91
Table V-14.	Gel Times (minutes) for Particleboard Made with Phenol-formaldehyde (PF) Resins Co-reacted with Urea .....	93
Table V-15.	Effect of Urea Addition on Dry and Wet Internal Bond Strengths in Softwood Particleboard Bonded Phenol-formaldehyde (PF) Resin .....	94
Table V-16.	Effect of Press Time on Dry and Wet Internal Bond Strength in Hardwood Particleboard Bonded with a Phenol-urea-formaldehyde (PUF) Resin with Triacetin .....	95
Table V-17.	Minimum American National Standards Institute (ANSI) Strength Requirements for Medium (M) Industrial and Shelving Grade Particleboard .....	97
Table V-18.	Strength Responses in Particleboard Made with Phenol-formaldehyde (PF) and Cashew Shell Nut Liquid (CNSL) Resins.....	98
Table V-19.	Density, Swell, Strength, and Formaldehyde Content in Medium Density Fiberboard Made with Urea-formaldehyde (UF) and Quebracho Tannin-based Resins .....	99
Table V-20.	Dry and Wet Internal Bond Strengths of Medium Density Fiberboard Made with Phenol-formaldehyde (PF) and Phenol-urea-formaldehyde-tannin (PUFT) Resins.....	100

Table V-21.	Proposed Phase 1 (P1) and 2 (P2) Formaldehyde (HCHO) Emission Standards for Hardwood Plywood.....	101
Table V-22.	Available Low-formaldehyde Hardwood Plywood (HWPW) or HWPW-Resins.....	103
Table V-23.	Proposed Phase 1 (P1) and 2 (P2) Emission Standards for Particleboard.....	104
Table V-24.	Available Low-formaldehyde Particleboard (PB) and PB-Resin Systems.....	104
Table V-25.	Proposed Phase 1 (P1) and Phase 2 (P2) Standards for Medium Density Fiberboard.....	105
Table V-26.	Available Low-formaldehyde Medium Density Fiberboard (MDF) or MDF-resins.....	106
Table VI-1.	Proposed Phase 1 and Phase 2 Standards for Hardwood Plywood (HWPW), Particleboard (PB), and Medium Density Fiberboard (MDF) .....	117
Table VI-2.	Schedule of Composite Wood Product Sell-through for Manufacturers.....	119
Table VI-3.	Schedule of Composite Wood Product Sell-through for Distributors.....	121
Table VI-4.	Schedule of Composite Wood Product Sell-through for Importers.....	123
Table VI-5.	Schedule of Composite Wood Product Sell-through for Fabricators.....	124
Table VI-6.	Schedule of Composite Wood Panel Sell-through for Retailers.....	126
Table VI-7.	Development Plan for Fully Covered Finished Products.....	127
Table VII-1.	Average and Elevated Formaldehyde Concentrations ( $\mu\text{g}/\text{m}^3$ ).....	133
Table VII-2.	Health Effects Values for Formaldehyde .....	133
Table VII-3.	Age-group Specific and Average Child and Adult Activity Patterns .....	156
Table VII-4.	Estimates of Total Formaldehyde (HCHO) Exposure and Daily Time-weighted Average (TWA) Formaldehyde Concentration .....	157
Table VII-5.	Estimated Cancer Risk in Children and Adults After Implementation of the Phase 1 and Phase 2 Emission Standards .....	158
Table VIII-1.	Particleboard Manufacturers in the Composite Panel Association .....	179

Table VIII-2.	Medium Density Fiberboard Manufacturers in the Composite Panel Association .....	181
Table VIII-3.	Hardwood Plywood Facilities in North America .....	182
Table VIII-4.	Cost per Plant by Type of Affected Product.....	186
Table VIII-5.	Change in Return on Owner’s Equity (ROEs) for Typical Manufacturers in the Composite Wood Products Industry .....	187
Table VIII-6.	Establishments, Employees, and Payroll by Industry .....	188
Table VIII-7.	Unit Cost of Industrial Particleboard: 1995-2005 .....	190
Table VIII-8.	Unit Cost of Medium Density Fiberboard: 1995-2005 .....	192
Table VIII-9.	Unit Cost of Hardwood Plywood .....	193
Table VIII-10.	Breakdown of Costs in Particleboard Manufacturing .....	197
Table VIII-11.	Estimated Cost of UF Resin in Particleboard of Varying Thickness.....	198
Table VIII-12.	Estimated Price Increase in Particleboard Made to Comply with the Phase 2 Standard with an Alternate Resin .....	199
Table VIII-13.	Estimated Cost of Urea-formaldehyde (UF) Resin in Medium Density Fiberboard (MDF) of Varying Thickness .....	202
Table VIII-14.	Estimated Price Increase in Medium Density Fiberboard Made to Comply with the Phase 2 Standard with an Alternate Resin .....	202
Table VIII-15.	Estimated Cost of the Urea-formaldehyde (UF) Resin in Hardwood Plywood of Varying Board Thickness .....	204
Table VIII-16.	Estimated Price Increases in Hardwood Plywood Made with Alternate Resins .....	204
Table VIII-17.	Estimated Cost of Particleboard, Medium Density Fiberboard, and Hardwood Plywood Panels Following the Effective Date of the Phase 2 Standard.....	214

## List of Figures

Figure III-1.	Annual Statewide Summary for Ambient Formaldehyde .....	23
Figure III-2.	Mean Ambient Formaldehyde Concentrations by Air Basin.....	24
Figure IV-1.	Types of Hardwood Plywood .....	42
Figure IV-2.	Plywood Manufacturing Process.....	43
Figure IV-3:	Schematic of a Particleboard Manufacturing Line.....	44
Figure IV-4.	Reaction between a Nucleophile (Nu) and Formaldehyde.....	46
Figure IV-5.	Addition of Urea and Formaldehyde to Form Hydroxymethylureas .....	48
Figure IV-6.	Condensation Reaction and Polymerization of UF Resins.....	48
Figure IV-7.	Addition Reaction for Phenol and Formaldehyde.....	50
Figure IV-8.	Phenol-formaldehyde (PF) Resin: Condensation Reaction .....	50
Figure IV-9.	Phenol-Formaldehyde Cross-linked Polymer.....	51
Figure IV-10.	Addition Reaction for Formaldehyde and Melamine .....	52
Figure IV-11.	Condensation Reaction of Hydroxymethylated Melamines.....	52
Figure IV-12.	Isocyanate and Water React to Produce a Urethane.....	54
Figure IV-13.	Reaction of an Amine and Isocyanate to Form a Substituted Urea .....	54
Figure IV-14.	Urethane Bridge and Substituted Ureas React with Isocyanates.....	55
Figure IV-15.	Polymerization of PVA .....	57
Figure IV-16.	Average Yield of Extractives from Different Woods and Barks ...	58
Figure IV-17.	The A-Ring Unit of a Tannin Compound.....	59
Figure V-1.	Polyurethane Cross-linking in a PF-MDI Hybrid Resin .....	81
Figure V-2.	Cationic Polyamidoamine-epichlorohydrin (PAE) .....	84
Figure V-3.	Effect of Reaction Time on the Dry and Water-Soaking-and Drying (WSAD) Shear Strength of Plywood Made with a Soy Protein Isolate-Kymene <sup>®</sup> Resin <sup>1</sup> .....	85
Figure V-4.	Dry Internal Bond Strengths for Oriented Strand Board made with PF and Soy-PF Resins .....	87
Figure V-5.	Wet Internal Bond Strengths for Oriented Strand Board Made with Phenol-formaldehyde (PF) and Soy-PF Resins.....	88
Figure V-6.	Chemical Structure of Hexamine .....	90
Figure V-7.	Chemical Structure of a Monoflavonoid Unit.....	90
Figure V-8.	Mole Ratios of Free Formaldehyde:Phenol in Phenol-urea- formaldehyde (PUF) and PUF-Tannin Resins .....	92
Figure V-9.	Chemical Structure of Triacetin.....	94

Figure V-10.	Chemical Composition of Cashew Nut Shell Liquid .....	98
Figure VIII-1.	Value (\$) of U.S. Imports of Particleboard from China: 1997 to 2006.....	191
Figure VIII-2.	Value (\$) of U.S. Imports of Medium Density Fiberboard from China: 1997 to 2006 .....	193
Figure VIII-3.	Value (\$) of U.S. Imports of Hardwood Plywood from China: 1997 to 2006.....	194

## **List of Appendices**

Appendix A	Proposed Regulation Order
Appendix B	Planning & Technical Support Division. 2007. Estimation of 2002 Formaldehyde Emission Inventory from Composite Wood Products. Draft Report
Appendix C-1	Summary of Refined Air Dispersion Modeling Using ISC3 of Formaldehyde from Composite Wood Product Exposure Scenarios
Appendix C-2	Composite Wood Product ATCM – Modeling Scenario No. 1: HCHO Emissions from Composite Wood Products Stored at a Warehouse Store
Appendix C-3	California Air Resources Board Memorandum: Vernon Hughes to James Aguila, 12 June 2006, RE: Air Quality Modeling of Emissions from Composite Wood Products
Appendix D	Basis for Formaldehyde Emission Factors
Appendix E	Estimation of the Amount of Composite Wood Products in a Home
Appendix F	Basis for Estimating Reductions in Daily Time-Weighted Average Formaldehyde Concentration
Appendix G	Calculations of Per Panel and Industry-wide Costs
Appendix H	Comparison of CARB Emission Standards to Other International Standards

## **Executive Summary**

The California Air Resources Board (CARB) staff is proposing to establish an Airborne Toxic Control Measure (ATCM) to reduce formaldehyde emissions from composite wood products. "Composite wood products" is a general term for wood-based panels made from wood plies, particles, or fibers that are bound together with a resin or adhesive. They include hardwood plywood, particleboard and medium density fiberboard. These products emit formaldehyde because the resins typically used to bond the wood materials contain formaldehyde. Emissions from these products result from the release of unreacted formaldehyde from the resins and from chemical degradation over time.

Composite wood products are sold in large volumes to California, and are among the highest formaldehyde emitting products used in everyday applications. In this regard, formaldehyde is emitted into the air from composite wood products at the panel manufacturing plant, fabrication facilities, new home construction, remodeling construction, truck, rail, and ship transportation, lumberyards, and through windows, doors, and ventilation systems in homes and other buildings. The proposed ATCM was developed in consideration of the results of a survey of panels produced in 2002, which indicated that actual formaldehyde emissions from U.S. composite wood products were much higher than those allowed in Europe, Japan, and Australia.

### **A. Background**

In 1992, the Board identified formaldehyde as a toxic air contaminant (TAC) based primarily on the determination that it was a human carcinogen with no known safe level of exposure (CARB, 1992). Because formaldehyde is a TAC, CARB is required to prepare a report on the need and appropriate degree of regulation to reduce formaldehyde emissions (Health & Safety Code §39665). Regulations that bring about reductions in TAC emissions are known as ATCMs. State law requires that ATCMs be based on the use of the best available control technology (BACT) or a more effective control method, in consideration of cost and human health risk (Health & Safety Code §39666), if the TAC has no safe level of exposure. Exposure to formaldehyde has both non-cancer and cancer health effects. The non-cancer health effects of formaldehyde are eye, nose, and/or throat irritation. The International Agency for Research on Cancer conducted an evaluation of formaldehyde and concluded that there is sufficient evidence that formaldehyde causes nasopharyngeal cancer in humans (i.e., in the region of the throat behind the nose).

Current emissions of formaldehyde from composite wood products are estimated to be about 900 tons per year. For the most part, formaldehyde emissions from these products are not regulated in the U.S.; although many manufacturers met an essentially voluntary standard established by the U.S. Department of Housing

and Urban Development (HUD) that applies to plywood and particleboard used in manufactured homes. Current annual average concentrations of formaldehyde in ambient air range from 3 to 4 micrograms per cubic meter ( $\mu\text{g}/\text{m}^3$ ) across California, with indoor and in-vehicle concentrations typically many times higher. The risk from exposure to annual average concentrations of formaldehyde in ambient air is about 20 to 24 potential excess cancer cases per million. The risk from current total daily formaldehyde exposure is estimated to range from 86 to 231 excess cancer cases per million over a lifetime, and from 23 to 63 excess cancer cases per million due to exposures during childhood. The proposed ATCM would reduce emissions to ambient air and very significantly reduce total daily exposures to formaldehyde. Exposures to formaldehyde, which occur throughout the day in both the outdoor and indoor environment, pose a serious health risk to the people of California.

## **B. Staff Proposal**

Because there is no safe threshold exposure level for formaldehyde, we are proposing a control measure to limit formaldehyde emissions from three composite wood products – hardwood plywood (HWPW), particleboard (PB), and medium density fiberboard (MDF) to the maximum amount feasible. Based on our survey results, these three products are still primarily being made with urea-formaldehyde resins that have the highest formaldehyde emission rates. Formaldehyde emission rates from other composite wood products (e.g., oriented strandboard, hardboard, peg board, etc.) used for exterior applications are about 90% lower and contribute far less to formaldehyde concentrations in California.

Hardwood plywood is made by gluing together hardwood plies, and used to make paneling, flooring, cabinets and furniture. Particleboard is made of wood fragments or particles glued together, and used to make countertops, cabinets, and floor underlayments. Medium density fiberboard is made of wood fibers glued together, and used to make furniture, cabinets, moldings, and door skins.

The proposed ATCM would reduce emissions of formaldehyde from HWPW, PB, and MDF panels, and finished goods, such as furniture and cabinets fabricated with those materials. The ATCM would apply to panel manufacturers, distributors, importers, fabricators, and retailers. We are excluding from the regulation architectural plywood, military specified plywood, plywood used inside of motor vehicles, and windows that contain small amounts of HWPW, PB, or MDF (i.e., less than 5% by volume of wood products).

The proposed ATCM would establish new formaldehyde emission standards in two phases for HWPW, PB, and MDF, and would also apply to finished goods or products utilizing those materials. The intent of the Phase 1 emission standards is to set an industry cap and to stop the low-cost, high-emitting products from

overseas that can no longer be sent to other markets from coming into California. The Phase 2 emission standards reflect the use of BACT (Table ES-1).

Beginning January 1, 2009, the proposed Phase 1 emission standards would become effective, starting with HWPW made with a veneer core (HWPW-VC), PB, MDF, and thin MDF (tMDF), followed by the standard for HWPW made with a composite core (HWPW-CC), six months later (Table ES-1). A separate standard is proposed for tMDF that considers the technological limitations specific to MDF made to be 8 millimeters or less. Beginning January 1, 2011, a comparable suite of increasingly more stringent Phase 2 formaldehyde emissions standards is proposed. All of the standards are maximum allowable or “cap” standards, and would apply to products made in the U.S. or imported from other countries. By “cap” standards, we mean standards that cannot be exceeded. Panel producers will need to operate routinely below the “cap” to ensure that they standards will always be met.

To ensure compliance with the proposed ATCM, panel manufacturers, foreign and domestic, would need to be “third party certified.” This requirement calls for independent formaldehyde emission testing of panels and manufacturing processes for all manufacturers that sell panels used in the California market. Third party certifiers would be required to be approved by the Executive Officer. As an incentive, manufacturers that use “no added formaldehyde” resins would not be required to conduct third party certification.

Table ES-1. Proposed Phase 1 and Phase 2 Emission Standards <sup>1</sup>					
----- Standard Concentrations (ppm) -----					
Phase 1 Formaldehyde Emission Standards					
Eff. Date	HWPW-VC	HWPW-CC	PB	MDF	tMDF
Jan 2009	0.08	-----	0.18	0.21	0.21
July 2009	-----	0.08	-----	-----	-----
Phase 2 Formaldehyde Emission Standards					
Eff. Date	HWPW-VC	HWPW-CC	PB	MDF	tMDF
Jan 2011	0.05	-----	0.09	0.11	-----
Jan 2012	-----	-----	-----	-----	0.13
July 2012	-----	0.05	-----	-----	-----
<sup>(1)</sup> “ppm” = parts per million; “Eff. Date” = effective date; “HWPW-VC” = hardwood plywood – veneer core; “HWPW-CC” = hardwood plywood – composite core; “tMDF” = thin medium density fiberboard (8-mm or thinner). “Standard Concentrations” are allowable limits based on measurements made using the American Standards & Testing Method E1333-96.					

To provide assurances of compliant products to downstream customers, manufacturers would be required to provide chain-of-custody records to their customers. An example of such a document would be an invoice that states that the composite wood products comply with applicable Phase 1 or Phase 2 emission standards. These would include the necessary information to track a composite wood product to its original manufacturer. Chain-of-custody documents must accompany all HWPW, PB, and MDF panels and finished goods made with those materials if sold to California.

Beginning in 2009, all PB, HWPW, and MDF offered for sale in California would be required to have a label on each panel or a designation on a bill-of-lading that specifies that the product complies with California formaldehyde emission limits. Composite wood product manufacturers would be required to verify product compliance with prescribed emission testing protocols (i.e., American Standards and Testing Method E1333-96).

Beginning in 2012, businesses that sell in California and utilize PB, HWPW, or MDF as a raw material to fabricate other products, would be required to use only products that comply with the California formaldehyde emission limit. Fabricators are also required to label each finished good or product and provide chain-of-custody documentation. Moreover, retailers of PB, HWPW, and MDF or products containing those materials, could only sell HWPW, PB, or MDF meeting the California formaldehyde emission limits or fabricated finished goods or products containing composite wood products compliant with the California formaldehyde emission limits, imported or domestic.

### **C. Options for Meeting the Proposed Emission Standards**

In 2001, staff initiated efforts to determine how formaldehyde emissions from HWPW, PB, and MDF could be reduced. The ATCM defines BACT as the emission limits in Table ES-1. In our analysis of potential BACT options, we initially found that there are “niche” products presently being sold with very low formaldehyde emissions. In addition, there are products being made with proprietary “no added formaldehyde” resins, such as resins made from soy flour.

In addition, we learned that manufacturers have an array of options for lowering formaldehyde emissions from the urea-formaldehyde resins that they presently use, or they could opt to use an alternative resin system. In addition to the manufacture of low-formaldehyde content materials, laboratory studies have shown that additives can be used to further lower formaldehyde emissions (e.g., melamine, hexamine) in panels made with urea-formaldehyde resins beyond those levels achieved with today’s use of additives. Alternatively, considerable work has been done to demonstrate the utility of tannin-based resins.

We believe that manufacturers will generally have more than one option for meeting the proposed formaldehyde emission standards. To produce products that meet the Phase 1 standards, we believe that manufacturers that choose to use urea-formaldehyde resins could comply by optimizing their current production processes and using resins with lower amounts of formaldehyde. Alternatively, manufacturers could opt to follow an alternative compliance option and use a “no added formaldehyde” resin, which could also allow for producing panels that immediately comply with the proposed Phase 2 standards in Table ES-1.

To meet the Phase 2 standards, we believe that manufacturers that choose to continue using urea-formaldehyde resins will need to make further changes. They would likely need to use additives such as melamine, in concentrations ranging from 8 to 15% by weight, to achieve the emission limits in Table ES-1. In terms of alternative resin systems, HWPW manufacturers could use polyvinyl acetate resins, which are already being used to make panels for Green Building Programs across the U.S. For PB, we believe that a promising alternative resin system is phenol-formaldehyde resin, which is the resin currently being used to produce exterior-grade products in the U.S.

#### **D. Emission Reductions and Health Benefits**

Within the category of area-wide sources, formaldehyde emissions from HWPW, PB, and MDF in California are estimated to be about 900 tons per year. The proposed Phase 1 emission standards for HWPW, PB, and MDF are about 66%, 49%, and 41% tighter, respectively, than the voluntary HUD-based standard met by many manufacturers. Based on the average emissions of existing products, the ATCM would reduce emissions of formaldehyde by about 20% in Phase 1. The proposed Phase 2 emission standards for HWPW, PB, and MDF are about 79%, 75%, and 69% tighter, respectively, than the voluntary HUD-based standard met by many manufacturers. Based on the average emissions of existing products, the ATCM would reduce emissions of formaldehyde by about 57% in Phase 2. This is an estimated annual emissions reduction of about 180 tons per year from Phase 1 and 500 tons per year from Phase 2.

Because these emissions would also substantially reduce indoor formaldehyde exposures, the largest benefit would be realized by buyers of new homes. Substantial benefits would also be realized by those in existing homes due to reduced emissions from new remodeling projects and newly purchased furniture. These reductions benefit ambient air quality as nearly all formaldehyde directly emitted indoors moves to the outdoors. Most of the formaldehyde moves outdoors within hours, primarily through indoor-outdoor air exchange from natural ventilation and building leakage. A very small amount of formaldehyde (< 1% up to 7%) is estimated to be removed through chemical reactions with other compounds in indoor air or on surfaces.

To estimate the reduction in cancer risk resulting from the implementation of the proposed Phase 1 and Phase 2 standards, we calculated the potential cancer risk from total formaldehyde exposures to current-average and current-elevated formaldehyde concentrations. In the two scenarios, average or elevated outdoor, indoor, and in-vehicle formaldehyde concentrations were obtained from the literature to estimate daily time-weighted average and elevated exposures, respectively. Based on projected decreases in daily average or elevated formaldehyde exposure, formaldehyde-related cancer risk in adults would be reduced by 35 to 97 excess cancers per million, over a 70-year lifetime exposure (Table ES-2). In children, it would result in a reduction of 9 to 26 excess cancers per million, based on a 9-year childhood exposure. Risk reductions would be far greater for those living in new or nearly new homes, where formaldehyde levels can be significantly higher.

Table ES-2. Estimated Reductions in Cancer Risk After Phase 1 and Phase 2 <sup>1</sup>			
A. Childhood Exposure: 9-year Exposure to Formaldehyde			
Exposure Scenario	TWA Formaldehyde	Cancer Risk Per Million	Cancer Cases Reduced
Current-average	16 µg/m <sup>3</sup>	23	-----
• Post Phase 1	13 µg/m <sup>3</sup>	20	3
• Post Phase 2	9 µg/m <sup>3</sup>	14	9
Current-elevated	42 µg/m <sup>3</sup>	63	-----
• Post Phase 1	36 µg/m <sup>3</sup>	54	9
• Post Phase 2	25 µg/m <sup>3</sup>	37	26
B. Lifetime Exposure: 70-year Exposure to Formaldehyde			
Exposure Scenario	TWA Formaldehyde	Cancer Risk Per Million	Cancer Cases Reduced
Current-average	16 µg/m <sup>3</sup>	86	-----
• Post Phase 1	14 µg/m <sup>3</sup>	74	12
• Post Phase 2	9 µg/m <sup>3</sup>	51	35
Current-elevated	42 µg/m <sup>3</sup>	231	-----
• Post Phase 1	36 µg/m <sup>3</sup>	196	35
• Post Phase 2	25 µg/m <sup>3</sup>	134	97
<sup>(1)</sup> "TWA formaldehyde" = Daily time-weighted average formaldehyde concentration. "Cancer Risk" = number of estimated chances per million of developing cancer in a 9- or 70-years.			

## **E. Estimated Costs**

HWPW, PB, and MDF panels that comply with the proposed Phase 1 and Phase 2 standards can be produced using a range of available options used today to minimize formaldehyde emissions. For Phase 1, estimated production cost increases for HWPW, PB, and MDF panels, were between 1% and 7%. For Phase 2, the increases were estimated to range between 8% and 30%. Based on these incremental per panel cost increases, the total cost to the industry was calculated. In Phase 1, this would average \$19 million per year. After full implementation of Phase 2, costs were estimated at \$127 million per year.

### **1. Hardwood Plywood Industry**

Presently, about 40% of HWPW produced for California complies with the proposed Phase 1 and Phase 2 standards. For the remaining 60%, we believe manufacturers could apply a range of low-cost modifications that have been proven to lower formaldehyde emissions. As only a modest amount of reduction is needed, we believe that the production cost of a Phase 1 compliant HWPW panel would be increased by about 1%, due almost entirely to the increase in cost for improving the urea-formaldehyde resin (i.e., would raise the production cost of a \$20 HWPW panel up to \$20.25).

For the proposed Phase 2 standard, manufacturers would likely choose to add additional scavengers, namely melamine or hexamine, to reduce formaldehyde emissions from panels made with urea-formaldehyde resins. Alternatively, selected manufacturers may choose to use polyvinyl acetate resins, which may require some minor upgrading of equipment. Through either option, it is estimated that the cost to produce a Phase 2 compliant HWPW panel would be increased by about 8% to 19% (i.e., would raise the production cost of a \$20 HWPW panel to a range of \$21.50 to \$23.75).

### **2. Particleboard Industry**

Based on the CARB survey of products manufactured in 2002, about 55% of PB produced in the U.S. already complies with the proposed Phase 1 standard, and only a small amount of specialty products (< 1%) complies with the proposed Phase 2 standard. For about 45% of U.S. production, we believe that to produce a panel with a urea-formaldehyde resin that complies with the Phase 1 standard, manufacturers would apply many of the same measures as noted previously for HWPW. By the same reasoning, it is estimated that the production cost of a Phase 1 compliant PB panel would be increased by about 4% to 7%, due almost entirely to the increase in resin cost (i.e., would raise the production cost of a \$10.50 PB panel to a range of \$11 to \$11.80).

For the proposed Phase 2 standards, manufacturers would likely use a melamine-urea-formaldehyde (MUF) resin in combination with the use of lower mole ratio urea formaldehyde resins (i.e. F:U<1). We believe that to meet the Phase 2 standard, the MUF resin would need to contain about 8% melamine by weight. In addition to increased resin costs, it was further assumed that processing times would be lengthened by about 10%. Thus, the cost to produce a Phase 2 compliant PB panel would be increased by about 17% to 30% (i.e., would raise the production cost of \$10.50 PB panel to a range of \$12.30 to \$13.80).

### 3. Medium Density Fiberboard Industry

Based on the CARB survey of panel products manufactured in 2002, about 25% of MDF produced in the U.S. already complies with the proposed Phase 1 standard, and only a small amount of specialty products (< 1%) complies with the proposed Phase 2 standard. For about 75% of U.S. production, manufacturers will likely apply similar modifications to their urea-formaldehyde resins, as noted for PB and HWPW. Thus, the cost of a Phase 1 compliant MDF panel would be increased by about 4% to 6%, due to the increase in resin cost (i.e., would raise the price of a \$14.00 MDF panel to a range of \$14.50 to \$15.00).

For the proposed Phase 2 standards, manufacturers would likely choose to use a melamine urea-formaldehyde resin with 12% melamine in combination with the use of lower mole ratio urea formaldehyde resins (i.e. F:U <1). In addition to increased resin costs, we assumed that processing times would be lengthened by about 30%. Thus, we believe that the cost to produce a Phase 2 compliant MDF panel would be increased by about 30% (i.e., would raise the price of a \$14.00 MDF panel to \$18.20). A few manufacturers produce MDF with pMDI, however pMDI is much more costly than urea formaldehyde resins (see Table VIII-14). The cost of an MDF panel made from (polymeric Methylene Diphenyl Diisocyanate) pMDI would be increased by about 135%, due to the increase in resin cost (i.e., would raise the price of a \$14.00 MDF panel to \$33). So, staff believes that manufacturers would opt to use the less expensive melamine fortified, low mole ratio urea-formaldehyde resin to meet the Phase 2 emission standard.

### 4. Total Combined Cost to the Industry

The above estimated “per panel” production cost increases were used to calculate the total cost to the HWPW, PB, and MDF industries and are shown in Table ES-3. Using production data for 2002, the total estimated cost in California are estimated to be about 19 million dollars annually to meet the Phase 1 standards and about 127 million dollars annually to meet the Phase 2 standards.

Table ES-3. Total Estimated Cost to the Industry in 2002			
Product	Production (Million Panels)	Phase 1 Annual Costs (Millions)	Phase 2 Annual Costs (Millions)
HWPW	9.3	6	17
PB	19.5	4	61
MDF	8.7	9	49
Total Estimated Cost	-----	19	127

#### 5. Consumer Costs

Most of the composite wood in a new home is used in cabinets, shelving, countertops, and moldings. The increased cost of composite wood products would have a limited effect on new home construction costs. Staff estimates that for a 2000 square foot home, the increased cost of construction is about \$390.00 for a medium priced house of \$574,000.00, the estimated price increase is 0.07 %.

Based on the estimated cost of meeting the phase 2 emission standards, the increase in the price of a panel would range from about \$3.00 to \$6.00, among various product types.

#### **F. Comments on the Staff Proposal**

Some manufacturers have expressed concerns about the stringency of the proposed Phase 2 standards and the amount of time they are provided to implement changes in their plants. We believe that the proposed standards are achievable with the application of one or several additives and through improvements in the manufacturing process. With respect to the amount of time needed to produce compliant products, we understand that most manufacturers that intend to sell to California have already begun research to develop new resin system(s). As the effective date of the ATCM is about two years into the future for Phase 1 and four years before Phase 2, we believe there is sufficient time for manufacturers to conduct mill trials and make the necessary production changes for their new or modified resin systems.

Another manufacturer has commented that the Phase 1 standards for HWPW should be lower and required sooner, and the Phase 2 standards should also be effective sooner than staff is proposing. We are not proposing earlier compliance dates because we believe that most HWPW manufacturers will need the provided time to research alternatives, and as appropriate, redesign their manufacturing operations. We are not proposing lower standards for Phase 1 because our intent is to set an industry cap to stop the low-cost, high-emitting products from coming into California.

## **G. Other Formaldehyde Emission Standards**

Presently, the U.S. trails the efforts undertaken in Japan, Europe, and Australia to reduce formaldehyde emissions from composite wood products. In Europe, concerns over the health effects of formaldehyde emissions from composite wood products led to a guideline to limit formaldehyde emissions from particleboards, fiberboards, and plywood to 0.1 ppm, which is known as the E1 classification (Deutsches Institut fur Bautechnik, 1994). Australia has also adopted the E1 classification. In Japan, the Japanese Building Standard Law (Takabatake, 2003) created a “sick house” regulation which regulates the amount of formaldehyde that can be emitted from building materials.

Staff believes that the proposed Phase 2 standards will limit formaldehyde as effectively or more effectively than those being applied elsewhere in Europe or Japan. In comparison to the proposed Phase 1 and Phase 2 standards, the E1 standard is an “average” standard that allows panels to be produced with formaldehyde contents higher than the value of the standard. The proposed ATCM is a “cap” standard which does not allow for any products with emission levels above the cap to be sold to California. To ensure that the panels never exceed the standards, manufacturers will need to routinely operate below the “cap.” Moreover, in terms of formaldehyde contents, Europe and Japan allow multiple grades of panels to be sold for consumer use. Therefore, not all panels in Europe and Japan meet a single standard. In Europe, a major portion is made to comply with less stringent standards than those proposed by staff, but in Japan, the F☆☆ and F☆☆☆ standards bracket the stringency of the proposed standards. In the proposed ATCM, all HWPW, PB, and MDF would be required to meet a single product-specific standard. The proposed ATCM would be the most stringent production standard in the world.

Unlike Europe and Japan, the U.S. has no comprehensive formaldehyde emission regulations for composite wood products. (The only standards are set by HUD, but apply only to manufactured homes.) Consequently, the U.S. is a growing market for low-cost, high-emitting products from overseas that can no longer be sent to other markets. While U.S. manufacturers have made progress toward lower formaldehyde emitting products since the 1980's, voluntary reduction efforts in the U.S. continue to lag far behind improvements being made in Europe and Japan. The proposed ATCM would apply to HWPW, PB, and MDF used in all other applications, there are no comparable federal regulations at this time. Note, however, that the HUD standard preempts other standards where it applies. Therefore, the proposed ATCM would not apply to manufactured homes.

## **H. Environmental Impacts**

The primary benefit of the proposed ATCM is a reduction in formaldehyde emissions, total public exposure, and excess cancer risk in California. In setting new formaldehyde emission standards for HWPW, PB, and MDF, reductions in statewide formaldehyde emissions of over 500 tons per year would be expected to occur at all points along the product distribution chain. In addition, we will request that the U.S. Environmental Protection Agency provide State Implementation Plan credits to California for the formaldehyde emission reductions from the ATCM. Formaldehyde is a volatile organic compound and a precursor to the formation of ozone. We anticipate no significant adverse environmental impacts from the implementation of this ATCM.

## **I. Environmental Justice**

The proposed ATCM would not cause significant adverse impacts in any community. Implementation of the proposed ATCM is aligned with the principle of pollution prevention, and would reduce exposures to formaldehyde in all communities, including low-income areas and ethnically diverse communities.

## **J. References**

California Air Resources Board (CARB). 1992. Final Report on the Identification of Formaldehyde as a Toxic Air Contaminant. Part A, Exposure Assessment. Technical Support Document, Stationary Source Division, Sacramento, CA. 89 pp.

Deutsches Institut für Bautechnik (DIBt). Guideline on the classification and control of wood-panels with regard to formaldehyde emission. Guideline 100, DIBt, Berlin, Germany. (English Translation; Original Not Seen)

Takabatake K. 2003. Japanese Sick House Regulations. Accessed: 6 July 2006. From: <http://strategis.ic.gc.ca/epic/site/imr-ri.nsf/en/gr116049e.html>

## I. Introduction

The California Air Resources Board staff is proposing an Airborne Toxic Control Measure to reduce formaldehyde (HCHO) emissions from composite wood products. “Composite wood products” is a general term for wood-based panels made from wood plies, particles, or fibers that are bound together with a resin or adhesive. They include hardwood plywood (HWPW), particleboard (PB) and medium density fiberboard (MDF), which emit HCHO because the resins typically used to bond the wood materials contain HCHO. Emissions from these products result from the release of unreacted HCHO from the resins and from chemical degradation over time. This chapter discusses our regulatory authority and the need for reducing HCHO emissions from composite wood products.

In the early 1980’s, the California Legislature approved Assembly Bill (AB) 1807 [Tanner, 1983] – also known as “The Toxic Air Contaminant Identification and Control Act.” Pursuant to AB 1807, the California Air Resources Board (CARB) established a comprehensive program to identify and control toxic air contaminants (TAC) to reduce public exposures to air toxics. Subsequently, the Legislature approved AB 2588 [Connelly, 1987], commonly known as the “Air Toxics “Hot Spots” Information and Assessment Act.” This legislation called for the development of a statewide inventory of air toxic emissions, requirements for notifying people exposed to significant air toxic-related health risks, and facility plans for reducing air toxic-related health risks.

In California’s TAC Identification and Control Program, CARB is required to consider specific criteria in its efforts to prioritize compounds for identification as TACs and for reducing statewide emissions (cf. Health and Safety Code (H&SC) §39660(f)). Moreover, data gathered under the AB 2588 “Hot Spots” program must also be evaluated. In 1992, CARB listed HCHO as a TAC without an identifiable threshold exposure level below which no significant adverse health effects are anticipated.

Because HCHO is a TAC, CARB is required to prepare a report on the need and appropriate degree of regulation to reduce HCHO emissions (H&SC §39665). Regulations that bring about reductions in TAC emissions are called airborne toxic control measures (ATCMs). State law requires that ATCMs be based on the use of the best available control technology (BACT) or a more effective control method, in consideration of cost and human health risk (H&SC §39666) for substances having no identified safe threshold.

This Initial Statement of Reasons (ISOR) for the proposed ATCM to control emissions of HCHO from composite wood products provides information on:

- The purpose of the regulation and CARB’s regulatory authority;
- The process and data used to develop the regulation;
- Physical and chemical characteristics of HCHO;

- Sources of HCHO;
- Annual average ambient HCHO concentrations, exposure, atmospheric persistence, and health effects;
- The major types of composite wood products used in California;
- How composite wood products are manufactured; and
- The proposed ATCM and its health, economic, and environmental impacts.

The proposed ATCM is designed to reduce the emissions of HCHO from HWPW, PB, and MDF, and finished goods that are fabricated with those materials. As HCHO is a carcinogen with no safe threshold exposure level, and because annual average ambient HCHO levels in California presently exceed the Office of Environmental Health Hazard Assessment's (OEHHA) chronic reference exposure level for HCHO, the proposed ATCM would reduce HCHO emissions to ambient air where there are existent risks to public health. Secondly, the proposed ATCM would also lower human exposures to HCHO in homes, schools, and workplaces, where indoor HCHO levels are also known to reach concentrations that pose serious health risks to sensitive individuals (e.g., children, the elderly, and people with pre-existing respiratory challenges).

#### **A. Regulatory Authority**

The Board's regulatory authority to control air pollution is set forth in Divisions 25.5 and 26 of the Health & Safety Code (H&SC). Health & Safety Code §39903 identifies CARB as:

“... the state agency charged with coordinating efforts to attain and maintain ambient air quality standards, to conduct research into the causes of and solutions to air pollution, and to systematically attack the serious problem caused by motor vehicles, which is the major source of air pollution in many areas of the state.”

Provisions in Division 26 of the H&SC authorize CARB to control the emissions of criteria pollutants (and their precursor) from specific source categories. For example, H&SC §41712 directs CARB to adopt regulations to reduce VOC emissions from consumer products. There are air pollutants, such as HCHO, that are precursors to criteria pollutants and are also TACs. TACs are defined in H&SC §39655 as:

“... an air pollutant which may cause or contribute to an increase in mortality or in serious illness, or which may pose a present or potential hazard to human health.”

The Board's authority to regulate TAC emissions is separately codified in H&SC §39650 et seq. (The “Tanner Act”), and in the case of compounds such as HCHO, the justification for pursuing emission reductions may derive from more than one provisions of the H&SC.

For the proposed ATCM, the authority of CARB to regulate HCHO emissions from composite wood products principally derives from the Tanner Act (H&SC §39650 et seq.). The Tanner Act established a two-step process to (1) identify and (2) control TACs in California. In the first step, a substance is formally identified as a TAC based on reviews by CARB and OEHHA. In the second step, CARB adopts appropriate regulations, such as ATCMs, to control TAC emissions and to reduce human exposure. In 1992, CARB identified HCHO as a TAC with no identified “safe” threshold exposure level (title 17, California Code of Regulations §93000.) In situations where no safe threshold level has been identified for a TAC, the Tanner Act requires CARB to reduce emissions of the TAC to the lowest level achievable through application of BACT or a more effective control method (H&SC §39666(c)).

In addition to the authority granted to CARB under the Tanner Act, H&SC §41712 provides CARB with supplementary, independent, authority to regulate HCHO emissions from consumer products (i.e., PB and MDF panels) as defined in Health & Safety Code §41712(a)(1) as:

“... a chemically formulated product used by household and institutional consumers ...”

By this definition, PB and MDF panels, but not HWPW panels or finished goods made with those materials, are consumer products because they are “chemically formulated” products that are produced by processing wood waste (e.g., sawdust and other waste wood) to form particles or fibers, which are then combined with resins and other chemicals to produce a panel product that is used by household and institutional consumers. While wood waste is one of the raw materials in the panel product, the wood is highly processed and the panel product is created by applying heat and pressure to induce chemical reactions between the proteins in wood and the resins and other chemicals added to the mixture (see subsection IV.C.) As PB and MDF are consumer products, H&SC §41712(b) requires CARB to adopt regulations to achieve the maximum feasible reductions in volatile organic compounds (VOCs) emitted by consumer products. Because HCHO is both a TAC and a VOC, under H&SC §41712, CARB has the authority to adopt HCHO emission standards for PB and MDF as a VOC control measure for consumer products.

## **B. Formaldehyde in California**

Formaldehyde is directly emitted from a variety of mobile, stationary, area-wide, and natural sources in California (see subsection III.B.). Composite wood products (i.e., HWPW, PB, and MDF) are responsible for about 5% of these emissions, and the emissions from these products occur both outdoors and indoors. Formaldehyde is emitted to ambient, outdoor air from newly made and standing stocks of composite wood products stored at manufacturing facilities, construction sites, and lumberyards, and during transport of composite wood products by rail, truck, or ship. Indoor emissions come from composite wood

products used as structural components or amenities inside buildings. Over time, studies demonstrate that HCHO emissions produced indoors from an array of sources, including composite wood products (Battelle, 1996), make their way outdoors through normal air exchange mechanisms (subsection III.F.), and contribute to concentrations measured in ambient air.

Ambient HCHO concentrations (i.e., outside) result from both direct HCHO emissions and from secondary HCHO formation in the atmosphere (see subsection III.C.). While the major mobile and stationary sources of direct HCHO emissions have previously been regulated by CARB or the U.S. Environmental Protection Agency (USEPA), composite wood products are an important source of HCHO emissions contributing to human exposure in California that have not yet been controlled. Presently, the statewide annual average HCHO concentration in ambient air exceeds the chronic reference exposure level for HCHO that presents a known risk to public health (OEHHA, 2005). Thus, reducing ambient HCHO concentrations is of principal concern from a public health perspective, requiring both reductions in directly emitted HCHO and in VOC emissions that contribute to secondary HCHO formation. Since the 1970's, CARB has adopted a suite of increasingly stringent VOC control measures for mobile sources as a means to substantially reduce VOC emissions, including HCHO, to achieve state and federal ambient air quality standards for ozone. Reducing VOC emissions has historically been a primary focus of state air quality regulators and reductions have been achieved from nearly every significant source of VOC emissions (CARB, 2007). In spite of these efforts, there is a continuing need for additional VOC control measures to garner the remaining VOC reductions needed to achieve state and federal ozone standards.

“Hot spots” are areas where concentrations of a TAC in ambient air, such as HCHO, are greater than regional or statewide average TAC concentrations. The elimination of “hot spots” has been the primary rationale for many of the ATCMs adopted by CARB in the past (e.g., CARB, 2006). In this regard, results from computer modeling analyses indicate that composite wood products may contribute to HCHO “hot spots” close to a range of sources where these products are present (subsection III.G.). The modeling results indicate that maximum HCHO concentrations in these “hot spots” represent a health risk to proximate receptors. This risk would be reduced by controlling HCHO emissions from composite wood products.

In addition to the health risk posed by HCHO in the ambient air, an additional health risk exists from indoor concentrations of HCHO. As indoor levels in many situations exceed outdoor levels, potential health risks to building occupants are likely to be greater. Although composite wood products contribute only a small percentage to the HCHO levels that occur in the ambient air, these products are responsible for a large portion of HCHO exposure that occurs indoors. These combined outdoor and indoor exposures lead to substantial total exposures to HCHO for adults and children.

### **C. Need for Reducing Formaldehyde Emissions from Composite Wood Products**

Formaldehyde is an air pollutant that is both a TAC and a precursor to the formation of ozone. In choosing to control HCHO emissions from composite wood products, staff considered four factors. As mentioned previously, one factor is that composite wood products are an important uncontrolled source of HCHO emissions. While there are a number of other sources of HCHO, there is no identified safe threshold exposure level and this ATCM contributes to reducing ambient HCHO to the lowest level achievable. Also, with respect to ambient air, the second factor considered by staff is that emissions from composite wood products contribute to ambient HCHO “hot spots,” such as in proximity to a lumberyard.

The third factor considered by staff is that controlling HCHO emissions from composite wood products will provide the greatest benefit in terms of reducing the total air pollution related health risk from HCHO. Recognizing that the Tanner Act requires CARB staff to consider all relevant factors, including the potential exposure to a TAC in indoor environments, in deciding what sources of HCHO to prioritize for regulation (H&SC §39660.5 and 39665), reducing HCHO emissions from composite wood products will dramatically reduce indoor health risks, and thus significantly reduce total exposure and risks from HCHO emissions in California. Thus, it is appropriate for the CARB staff to give priority to developing an ATCM for this source of HCHO.

The fourth factor considered by staff is that significant VOC reductions that would be achieved in setting stringent HCHO emission standards for composite wood products. The reductions from this source category are part of the CARB’s overall effort to establish VOC standards for numerous categories of consumer products. Because California needs VOC emission reductions to achieve state and federal ambient air quality standards, it has been necessary to develop standards for products from which very low levels of emissions reductions could be achieved (e.g., limits on contact adhesives effected 11 tons per year of VOC emission reductions) (CARB, 2004). As HCHO is also a VOC, the proposed ATCM would reduce HCHO emissions from HWPW, PB, and MDF by approximately 500 tons per year after adoption of the Phase 2 standards in 2012. Moreover, HCHO is a highly reactive VOC, which means that any reduction in HCHO emissions will have an impact in reducing ozone formation. Because of its high reactivity, the benefits of reducing HCHO emissions will be much greater than for other VOCs that are less reactive.

## **D. Regulations Applicable to Formaldehyde**

### **1. Airborne Toxic Control Measures**

No specific ATCM to control HCHO emissions has been adopted by CARB, since HCHO was identified as a TAC in 1992. However, HCHO emissions from mobile sources have been reduced as a result of regulations that lower exhaust emissions of non-methane hydrocarbons from vehicles in light-duty, medium-duty, and heavy-duty weight classifications. In addition, exhaust emission standards limiting formaldehyde emissions have been established.

### **2. Comparable Federal Regulations**

The USEPA identified HCHO as a hazardous air pollutant (HAP) in the federal Clean Air Act Amendments of 1990. In 1992, CARB formally identified HCHO as a TAC (CARB, 1992).

In 1985, the U.S. Department of Housing and Urban Development (HUD) established HCHO emission limits for PB and HWPW used to construct mobile homes (Newton et al., 1986). As the standards apply only to PB and HWPW, and specifically when used in the manufacture of mobile homes, they in effect apply to a niche product, and not to composite wood products for use in other applications. These standards were instrumental in actuating substantial HCHO emission reductions in PB and HWPW which are bonded with urea-formaldehyde resins. However, exposures to HCHO in indoor settings, including but not limited to mobile homes, can still be found at levels that posed significant health risks (CARB, 2005), even after the HUD requirement for the use of lower-emitting composite wood products.

To control air toxic emissions in the USEPA's National Emission Standards for Hazardous Air Pollutants Program, toxic emission limits were established for plywood and other composite wood product manufacturing facilities (USEPA, 2002). This rule applies to emissions generated at manufacturing facilities, but does not apply to emissions from the products themselves.

While federal statutes have been enacted to control HCHO emissions from HWPW and PB for use in mobile homes and from composite wood product manufacturing facilities, there is no comparable, existing federal regulation to the proposed ATCM.

### **3. Safe Drinking Water and Toxic Enforcement Act of 1986**

Formaldehyde was listed as a carcinogen on January 1, 1988, under the Safe Drinking Water and Toxic Enforcement Act of 1986 (i.e., Proposition 65), which requires the State to publish a list of chemicals known to cause cancer, birth

defects, or other reproductive effects (OEHHA, 2005). The list is updated at least once a year, and currently includes over 750 chemicals.

### **E. Indoor Air Quality**

With respect to air pollution, a principal responsibility of state and federal environmental protection agencies is to protect public health by ensuring the air is clean. Since the 1970's, substantial reductions in ambient air pollutant levels have been realized through efforts aimed at lowering emissions from motor vehicles, stationary sources, and many other sources. While these efforts have been beneficial to public health in California and the rest of the nation, studies have found that people spend 90% or more of their time indoors (University of California, Berkeley, 1991), where less is known about the sources of indoor air pollution or the potential health risks that could be occurring.

In the early 1990's, CARB released an indoor air quality guideline titled "Formaldehyde in the Home," which identified the major sources of HCHO in homes and what people could do to reduce indoor HCHO exposures (CARB, 1991). Composite wood products such as PB, HWPW, and MDF were listed as major sources of HCHO emissions in California homes, where average HCHO concentrations were reported to be 70 to 80 and 50 parts per billion (ppb) in mobile and conventional homes, respectively. Subsequent research confirmed the importance of composite wood products as a source of HCHO in indoor environments (Battelle, 1996), which in combination with HCHO emissions from other consumer goods and products, allowed for intermittent exposures well above levels determined to cause chronic health effects (OEHHA, 2005). These same concerns were reiterated in a recent report to the California Legislature titled "Indoor Air Pollution in California," submitted in response to the requirements of AB 1173 [Keeley, 2002] (CARB, 2005).

### **F. References**

Battelle. 1996. Determination of Formaldehyde and Toluene Diisocyanate Emissions from Indoor Residential Sources. Final Report, CARB Contract No. 93-315, Sacramento, CA. 119 pp.

California Air Resources Board (CARB). 1991. Formaldehyde in the Home. Indoor Air Quality Guideline, Research Division, Sacramento, CA. 5 pp.

CARB. 1992. Final Report on the Identification of Formaldehyde as a Toxic Air Contaminant. Part A, Exposure Assessment. Technical Support Document, Stationary Source Division, Sacramento, CA. 89 pp.

CARB. 1993. The Identification of Federal Hazardous Air Pollutants as Toxic Air Contaminants. Staff Report, Stationary Source Division, Sacramento, CA. 8 pp.

CARB. 2004. Initial Statement of Reasons for the Proposed Amendments to the California Aerosol Coating Products, Antiperspirants and Deodorants, and Consumer Products Regulations, Test Method 310, and Airborne Toxic Control Measure for Para-dichlorobenzene Solid Air Freshener and Toilet/Urinal Care Products. Stationary Source Division, Sacramento, CA.

CARB. 2005. Indoor Air Pollution in California. Report to the Legislature, Pursuant to Health & Safety Code §39930. Research Division, Sacramento, CA. 248 pp.

CARB. 2006. Proposed Amendments to the Hexavalent Chromium Airborne Toxic Control Measure for Chrome Plating and Chromic Acid Anodizing Operations. Stationary Source Division, Sacramento, CA. 125 pp.

CARB. 2007. Air Resources Board's Proposed State Strategy for California's 2007 State Implementation Plan. Draft Report, Planning & Technical Support Division, Sacramento, CA. From: <http://www.arb.ca.gov/planning/sip/sip.htm>  
Accessed: 14 February 2007.

Newton LR, WH Anderson, HS Lagroon, and KA Stephens. 1986. Large-scale test chamber methodology for urea-formaldehyde bonded wood products. In: B Meyer, BA Kottes Andrews, and RM Reinhardt (eds). Formaldehyde Release from Wood Products. ACS Symposium Series No. 316: 154-187.

OEHHA. 2005. Proposition 65 in Plain Language. Accessed: 8 February 2007.  
From: <http://www.oehha.ca.gov/prop65/background/p65plain.html>

U.S. Environmental Protection Agency (USEPA). 2002. Regulatory Impact Analysis of the Proposed Plywood and Composite Wood Products NESHAP. Final Report, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

University of California, Berkeley. 1991. Activity Patterns of California Residents. Final Report, CARB Contract No. A6-177-33, Research Division, Sacramento, CA. 63 pp.

## II. Public Outreach

This chapter summarizes the numerous public meetings held with stakeholders since fall 2001 when plans were announced to develop an ATCM to reduce HCHO emissions from composite wood products.

### A. Outreach Efforts

Table II-1 lists selected key public meetings, conference calls, or presentations to discuss various aspects of the proposed ATCM to reduce HCHO emissions from composite wood products. The meeting notices and related information are posted at: <http://arb.ca.gov/toxics/compwood/workshops.htm>.

Table II-1. Selected ATCM-related Outreach Efforts	
Date	Purpose of Meeting/Activity
Sep 2001	<ul style="list-style-type: none"> <li>Initial public meeting on proposed ATCM concept</li> </ul>
Oct 2001	<ul style="list-style-type: none"> <li>Focused meeting with non-manufacturer groups</li> </ul>
Nov 2001	<ul style="list-style-type: none"> <li>Public meeting on format and content of the product survey</li> </ul>
Jan 2002	<ul style="list-style-type: none"> <li>Focused meeting to refine the product survey</li> </ul>
Apr 2003	<ul style="list-style-type: none"> <li>Distribute survey to U.S. manufacturers</li> </ul>
Apr 2004	<ul style="list-style-type: none"> <li>Stakeholder meeting to discuss survey results</li> </ul>
Aug 2004	<ul style="list-style-type: none"> <li>Public meeting on survey results and need for ATCM</li> </ul>
Oct 2004	<ul style="list-style-type: none"> <li>Public meeting on ATCM data needs and enforcement</li> </ul>
May 2006	<ul style="list-style-type: none"> <li>Public meeting to release first draft regulation</li> </ul>
Jun 2006	<ul style="list-style-type: none"> <li>Public meeting on enforcement and revised draft regulation</li> </ul>
Aug 2006	<ul style="list-style-type: none"> <li>Site-visit to a particleboard manufacturing plant</li> <li>Site-visit to the Port of Oakland</li> </ul>
Sep 2006	<ul style="list-style-type: none"> <li>Presentation at National Green Building Conference</li> </ul>
Oct 2006	<ul style="list-style-type: none"> <li>Site-visit to architectural plywood facilities</li> <li>Conference call – Finished Product Testing</li> <li>Public meeting to release second revision of draft regulation</li> </ul>
Nov 2006	<ul style="list-style-type: none"> <li>Meeting with wood importing association</li> </ul>
Dec 2006	<ul style="list-style-type: none"> <li>Site-visits to a testing lab and plywood manufacturing plant</li> </ul>

### B. Public Involvement

Manufacturers, industry associations, government agencies, researchers, and environmental organizations were contacted and asked to provide input throughout the ATCM development process. In addition to hosting public meetings, information (e.g., meeting notices, slide presentations) was posted on ARB's website at: <http://www.arb.ca.gov/toxics/compwood/compwood.htm>. A composite wood list-serve was developed to keep approximately 540 stakeholders notified of progress being made with respect to ATCM

development. In addition, as specified in Health & Safety Code §39665(c), relevant comments on the ATCM have been included in the administrative record. Comments are listed as a reference to the chapter, and are available from CARB staff upon request (Various, 2005-2007).

## **1. Industry**

Manufacturers and industry associations have been active participants throughout the ATCM development process. Their involvement has included:

- Contacting staff by telephone and email;
- Providing facility tours;
- Responding to the 2003 Composite Wood Survey; and
- Participating in conference calls and public meetings.

In 2006, a major effort was initiated to open a dialogue with industry associations and individual manufacturers, fabricators, and retailers. In addition to the three public workshops (Table II-1), the outreach effort included over 30 face-to-face meetings, over 20 conference calls, approximately 10 facility site-visits, and two presentations at national conventions/conferences. Among the industry associations that were contacted and/or provided input during the ATCM development process are:

- American Home Furnishings Alliance
- American Homeowners Association
- APA – The Engineered Wood Association
- Australian Wood Panels Association, Inc.
- Business & Industrial Furniture Manufacturers Association
- California Building Industry Association
- California Manufactured Housing Institute
- California Wood Industries Coalition
- Composite Panel Association
- Consulate General – People’s Republic of China
- Door & Access System Manufacturers Association
- Forintek Canada Corporation
- Formaldehyde Council, Inc.
- Formaldehyde-free Coalition
- Hardwood Plywood & Veneer Association
- Healthy Building Network
- International Wood Products Association
- Kitchen Cabinet Manufacturers Association
- National Retail Federation
- National Wood Flooring Association
- Window & Door Manufacturers Association
- Woodwork Institute

In addition, meetings and conference calls with a number of individual companies were held throughout 2006. Through these contacts, it was learned that the proposed California regulations were being discussed at international wood products meetings in Asia and Europe. While the proposed ATCM has the potential to impact many economic sectors, a concerted effort was made to contact and solicit input from as many affected industries as possible.

## **2. Government Agencies**

In addition to consulting with CARB staff in the Enforcement, Monitoring and Laboratory, Planning and Technical Support, and Research Divisions, input and cooperation was received from other State agencies and local air districts. Concerning issues related to health risk assessment, numerous meetings and conference calls were held with the OEHHA to seek their input on the methodology used to assess health risks for the proposed ATCM. Similarly, regular updates were provided to the California Air Pollution Control Officers Association's (CAPCOA) Toxic Air Risk Managers Advisory Committee on progress made on ATCM development. A separate presentation was also made to CAPCOA's Enforcement Managers.

Owing to the nature of the HCHO emission test procedures used in the composite wood products industry, contacts were made with the California Department of Health Services, which is in the process of developing a test facility in their San Francisco Bay Area Laboratory that would be comparable to test facilities operated by the Composite Panel Association and the Hardwood Plywood & Veneer Association, the principal industry associations in the U.S. An agreement is being developed to utilize the test facility that will be operated by the Department of Health Services.

### **C. Survey of Products Manufactured in 2002**

A survey was conducted in 2003 to gather data on composite wood products manufactured in 2002. In 2003, a survey package was sent to over 200 U.S. manufacturers (<http://www.arb.ca.gov/toxics/compwood/survey2002.htm>). Manufacturers were asked to provide information about the range of products they produced, types of resins they used, amount of product sales in California, chemical composition of the resins used, and equipment used in manufacturing (CARB, 2003). Fifty-seven responses were received, and those data were analyzed and presented at a public meeting in August 2004. Results of the survey are discussed in detail in Chapter V.

## **D. References**

California Air Resources Board. 2003. Composite Wood Survey Package.  
From: <http://www.arb.ca.gov/toxics/compwood/survey.htm> Accessed: 8 February 2007.

Various. 2005-2007. Collection of Relevant Comments Concerning the Proposed ATCM to Control Formaldehyde Emissions from Composite Wood Products. Compiled by Stationary Source Division, Sacramento, CA.

### **III. Need for Regulation of Formaldehyde**

Under Health and Safety Code Section 39665, ARB is required to prepare a report on the need and appropriate degree of regulation for compounds identified as toxic air contaminants. This chapter meets the requirements of State Law and provides an overview of the physical and chemical properties of formaldehyde, sources, emissions, measured concentrations in various environments, and atmospheric persistence.

#### **A. Health Effects of Formaldehyde**

Exposure to HCHO has both non-cancer and cancer health effects. The non-cancer health effects of HCHO are eye, nose, and/or throat irritation (OEHHA, 2005b). In 2004, the International Agency for Research on Cancer conducted an evaluation of formaldehyde and concluded that there is sufficient evidence that HCHO causes nasopharyngeal cancer in humans (i.e., in the region of the throat behind the nose) (National Cancer Institute, Not Dated). The risk from exposure to annual average HCHO concentrations in ambient air alone is about 20 to 24 excess cancer cases per million based on a 70 year lifetime exposure. The number of excess cancer cases per million rises considerably when HCHO exposure from current total daily HCHO exposure is considered. A detailed, comprehensive review of the non-cancer and cancer health effects of HCHO is contained in Chapter VII.

#### **B. Physical and Chemical Properties**

Formaldehyde (HCHO) is a colorless, volatile, flammable gas at room temperature and pressure. It has a pungent, highly irritating, suffocating odor and may cause a burning sensation to the eyes, nose, and lungs at high concentrations. Pure HCHO is not available commercially and is generally produced, sold and transported as water solutions (formalin) with concentrations ranging from 25 to 56 weight percent (%) (Gerberich and Seaman, 1994). It is very soluble in water, alcohols and other polar solvents (Lide, 1999). Table III-1 summarizes some of the physical and chemical properties of HCHO.

Formaldehyde is also known as methanal, methylene oxide, oxymethylene, methylaldehyde, and oxomethane (USDHHS, 1999). The commercial forms of formaldehyde include paraformaldehyde, formalin solutions, polymers, resins, and other derivatives.

Formaldehyde is a member of the family of aldehydes, its simple structure is composed of two hydrogens directly attached to a carbonyl group (Wade, 1999). Formaldehyde exhibits most of the general chemical properties of aldehydes, except it is more reactive than longer chain aldehydes. Formaldehyde is a very strong electrophile. It can participate in electrophilic aromatic substitution reactions with aromatic compounds and can undergo electrophilic addition reaction with alkenes. Compared to other carbonyl compounds, HCHO has good

thermal stability and is able to undergo a broad range of chemical reactions, many of which are useful in commercial processes (CARB, 1992).

Formaldehyde gas can undergo slow polymerization to trimer, trioxane, and paraformaldehyde at temperatures below 80 °C (Canadian Centre for Occupational Health & Safety, 2005; Reuss et al., 1988). In aqueous solutions, HCHO reacts with water to form methylene glycol (CARB, 1992). Traces of polar impurities, such as water, methanol, alkalis, and acids considerably speed up the polymerization process (Reuss et al., 1988; Walker, 1964).

When pure liquid HCHO is warmed to room temperature in a sealed container it undergoes rapid polymerization with evolution of heat (Gerberich and Seaman, 1994). In order to prevent polymerization of HCHO, methanol is generally added as a stabilizing agent (Merck, 1989). The uncatalyzed decomposition of HCHO is slow (below 300 °C), which yields carbon monoxide and hydrogen gas (Gerberich and Seaman, 1994). When catalyzed by metals such as platinum, copper, chromia, and alumina, HCHO decomposition can produce methanol, methyl formate, formic acid, carbon dioxide, and methane. Formic acid is formed when HCHO is oxidized via atmospheric oxygen. When stored, HCHO solutions should be kept tightly sealed in order to prevent formic acid formation.

Table III-1. Physical and Chemical Properties of Formaldehyde <sup>1</sup>	
Chemical Formula:	HCHO
CAS Registry Number:	50-00-0
Molecular Weight:	30.03
Boiling Point:	-19.5 °C
Melting Point:	-118 °C
Vapor Pressure:	3284 mm Hg at 20 °C
Vapor Density:	1.03 (aq); 1.08 (gas)
Density/Specific Gravity:	1.067 (air = 1)
Log Octanol/Water Partition Coefficient:	0.35
Conversion Factor:	1 ppm = 1.23 mg/m <sup>3</sup>
Solubility in Water:	Very soluble (40g/100mL at 20 °C)
<sup>(1)</sup> Sources: Canadian Centre for Occupational Health & Safety (2005); Merck (1989); Sax and Lewis (1989); Syracuse Research Corp. (2004).	

### C. Sources and Emissions of Formaldehyde

Formaldehyde gas is released into the environment from a variety of sources. There are directly emitted sources and there are indirect sources. Direct sources include motor vehicles, aircraft, boats, chemical plants, and fireplaces (see

subsection III.C.1). Indirect sources include atmospheric photooxidation processes, which is the dominant source of HCHO in the lower atmosphere. The photochemical oxidation of hydrocarbons in polluted atmospheres that contain ozone and nitrogen oxides results in formation of HCHO. This is the largest source of HCHO in ambient air in California (CARB, 1992).

Formaldehyde is the most commercially important aldehyde and it is an essential component of many resin technologies. More than half of all HCHO is used primarily to make urea-, phenol-, melamine-formaldehyde and polyacetal resins (Formaldehyde Council, Inc., 2005). Formaldehyde-based resins are used as adhesives for composite wood products including HWPW, PB, and MDF. Formaldehyde is widely used in mobile and conventional home construction, and in the garment industry. It can be found in products such as antimicrobial agents and it is also used in fumigants and soil disinfectants (USDHHS, 1999). As a result, these activities emit significant amounts of HCHO into surrounding air. Some of the uses of HCHO are summarized in Table III-2.

Table III-2. Product Distribution for Formaldehyde in the U.S. (2003) <sup>1</sup>	
Product	Percentage of consumption
Urea Formaldehyde Resins*	27
Phenolic Resins*	20
Polyacetal Resins*	11
Butanediol	9
Methylene Diisocyanate (MDI)	8
Pentaerythritol	4
Urea Formaldehyde Concentrates	3
Hexamethylenetetramine	2
Melamine Resins*	3
Miscellaneous	14

(<sup>1</sup>) Source: Global Insight, Inc. (2006). “\*\*” indicates products used in the manufacture of composite wood products. Note: Total may not add up to 100% due to rounding.

With respect to composite wood products, HCHO is directly emitted from manufacturing plants during panel processing and from fabrication facilities that use these products to make furniture, cabinets, etc. As HCHO emissions from composite wood products occur over multiple year periods, and throughout their distribution and use, substantive amounts of emissions occur during:

- Truck, rail, and ship transportation during product distribution;
- Use in new home construction and remodeling construction;
- Stockpiles in lumberyards and wood product warehouses; and

- Exchange processes from indoors to outdoors through windows, doors, and ventilation systems in homes and other buildings.

## 1. Outdoor Sources

Among the principal, directly-emitted sources of HCHO is the combustion of fossil fuels from mobile sources, which comprises nearly 76% of direct HCHO emissions (Table III-3). Of this total, nearly 26% of total statewide HCHO emissions originate from automotive exhaust (CARB, 2006a; Canadian Centre for Occupational Health & Safety, 2005). The remaining 50% can be attributed to airplanes, recreational boats, construction, and mining equipment (CARB, 2006a). Stationary sources comprise approximately 13% and area-wide sources, such as wood burning add approximately 11% to the overall statewide HCHO emissions. Other important, direct outdoor sources include power plants, agricultural burns, oil refineries, incinerators, and tobacco smoke.

Table III-3. Formaldehyde – 2005 Statewide Emission Inventory <sup>1</sup>		
Emission Source	Tons/Year	Percent of Total
Stationary	2,474	12
Area-wide	2,014	10
On-Road Mobile	4,999	25
Gasoline	3,076	15
Diesel	1,922	10
Other Mobile	9,590	48
Gasoline	2,979	15
Diesel	4,526	23
Other	2,085	10
<b>Composite Wood</b>	<b>900</b>	<b>5</b>
Natural Sources	0	0
Total Statewide	19,978	100
<p><sup>(1)</sup> Source: CARB (2006a) for all tons/year values <u>except</u> “Composite Wood.” The tons/year value for composite wood is a preliminary estimate based on Appendix B. Note: Totals may not add up due to rounding.</p>		

Other anthropogenic sources of HCHO include industrial releases of HCHO at any given stage of the production, use, storage, transport, or disposal of products with residual HCHO (Liteplo et al., 2002).

## 2. Indoor Sources

Generally, indoor HCHO concentrations are higher than outdoor concentrations due to the wide spectrum of building materials and consumer products in

workplaces and residential areas that emit HCHO (CARB, 1992; USDHHS, 1999). Formaldehyde resins are used in many materials and these resins slowly give off HCHO over time. Off-gassing from construction and building materials, especially composite wood products made with urea-formaldehyde (UF) resins and spray-on insulating foam are primary sources of indoor HCHO emissions. Other potentially significant sources of HCHO in indoor areas are tobacco smoke, wood-burning stoves, fireplaces, and furnaces (CARB, 1992). Textile products, carpet, pads and tape, drapes, and a vast number of consumer products also contribute to indoor HCHO concentrations (CARB, 2005b). While these emissions originate in indoor environments, the major portion of these emissions are removed to outside, ambient air by normal ventilation processes (e.g., when air moves through windows or doors, or mechanical ventilation systems), within a few hours.

a. Composite Wood Products

Newly manufactured composite wood products such as HWPW, PB, and MDF are the most significant sources of HCHO inside of homes (CARB, 2005b). Particleboard is used as sub-flooring, shelving material, as well as in cabinetry and furniture. Hardwood plywood paneling is commonly utilized for decorative wall coverings. Hardwood plywood is used in cabinets, furniture, and flooring. Medium density fiberboard is used for drawer fronts, cabinets, and furniture tops. Emission rates of selected indoor sources of HCHO are presented in Table III-4. The products tested were those used most commonly in the California market. The results showed that bare urea-formaldehyde composite wood products were the highest dry product emitters. The adhesive component of composite wood products (UF resin) is primarily responsible for the off-gassing of HCHO into the air. When these wood products are pressed in the manufacturing process, some unreacted UF resin and other volatiles are trapped within the boards, and released to air over time. Typically HCHO concentrations in the core of a composite wood panel are twice as high as that at the surface (USDHHS, 1999). Unreacted hydroxy-methyl groups that are inherently present in UF resins can also produce HCHO by hydrolytic cleavage.

Table III-4. Emission Rates of Selected Indoor Sources of Formaldehyde ( $\mu\text{g}/\text{m}^2/\text{hr}$ ) <sup>1</sup>	
Source of Formaldehyde	Emission Rate
Bare Urea-Formaldehyde Wood Products	8.6 to 1,580
Coated Urea-Formaldehyde Products	< 2.7 to 460
Permanent Press Fabrics	42 to 215
Decorative Laminates	4 to 51
Fiberglass Products	16 to 32
Bare Phenol-Formaldehyde Wood Products	4.1 to 9.2
Paper Grocery Bags and Towels	< 0.6
Latex Paint	502
Fingernail Hardener	215,500
Nail Polish	20,700
Base Coat Floor Finish	1,050,000
Top Coat Floor Finish	421,000
<sup>(1)</sup> Source: Battelle (1996). " $\mu\text{g}/\text{m}^2/\text{hr}$ " = microgram per square meter per hour. Values for wet products are average initial emissions.	

Principally, the release of HCHO is highest from newly manufactured wood products; however, the emission is strongly dependent on the nature of the material. As the products age, emissions of HCHO decrease over time to lower rates, thus older homes generally have lower indoor HCHO levels (CARB, 1992; Sexton et al., 1989). Formaldehyde emissions from composite wood materials have been measured in mobile homes and found to be greater than in conventional homes as a result of higher loading ratios (i.e., the ratio of the surface area of a source, such as a PB panel, to the volume of the enclosed area where the source is present). Meyer and Hermanns (1985) found that mobile homes have minimal ventilation and poorly insulated features, and thus, experience elevated HCHO levels due to the higher ambient temperatures where they are located.

b. Insulation Products

Urea-formaldehyde foam insulation (UFFI) previously was a major source of HCHO emissions that was addressed in the 1980's. In the early 1970's, UFFI was injected into wall cavities to improve the energy efficiency of older homes (Meek et al., 1985). Due to continuous health concerns, adverse acute and chronic health problems arose from the HCHO emissions that occurred during this time, and the U.S. Consumer Products Safety Commission placed a ban on UFFI in 1982. Although this ban was overturned, this action significantly contributed to a reduction in HCHO emissions and the residential use of UFFI

products. The California Energy Commission adopted insulation standards in 1982, which granted the use of UFFI only if its emissions were below 0.01 % by weight in a standard test protocol (CARB, 1992). This rule effectively prohibits the use of UFFI in California. Studies have shown that HCHO released from UFFI products decreased rapidly in the first few months and progressively declines with time. Thus, HCHO concentrations in older homes from insulation materials are likely to be low after several decades of product off-gassing.

c. Furnishings

There are many furnishing products that contain HCHO resins, and thus, have the potential to emit HCHO. Furniture constructed with PB and wood veneer emits HCHO. Formaldehyde polymers are used in the manufacture of floor coverings. Pre-pasted wall paper and papers that consist of fibers or layers that are bonded with HCHO resins also have HCHO-emitting potential (Gammage and Gupta, 1984). Formaldehyde-based resins are commonly used in the textile industry; they are used to produce crease-resistant and flame-retardant fabrics, and fabrics that withstand shrinking. Formaldehyde-releasing agents also provide dimensional stability and serve as binders in textile printing.

d. Cigarette Smoke

Sterling et al. (1987) measured HCHO in office buildings where smoking was permitted and found levels to be as high as 0.60 ppm. In comparison, non-smoking office buildings had levels as high as 0.22 ppm. Although composite wood products contribute to the majority of HCHO emissions in indoor air (Battelle, 1996), environmental tobacco smoke may also be a source of 10 to 25% of the noxious exposure (Sterling et al., 1987).

e. Consumer Products

Formaldehyde is also found in varying quantities in selected consumer products such as nail care products, adhesives, and paper products. Fabrics can be treated with HCHO-containing compounds, where it is used to add permanent press qualities to clothing and draperies. Paper products, such as grocery bags, napkins, paper towels, and disposable sanitary products are often treated with HCHO-containing resins which improve strength and water resistance (Gammage and Gupta, 1984). These consumer products contribute minimally to the HCHO concentrations of indoor air.

**D. Emissions from Composite Wood Products**

Prior to this rulemaking, HCHO emissions from composite wood products were not specifically estimated due to a scarcity of information on HCHO emission rates, rates of decay in emissions over time, and the amount of product sold each year into the California marketplace. Based on efforts to quantify the extent of emissions from composite wood products in the state, staff identified

composite wood products as a separate category of area-wide sources of HCHO (Appendix B).

## **1. Emissions Inventory**

Area-wide sources are source categories associated with human activity that take place over a wide geographic area (CARB, 2004). For purposes of the statewide emissions inventory for toxic air contaminants, composite wood products (i.e., HWPW, PB, and MDF) were classified as an “aggregated point source,” which consists of many small point sources, which are not inventoried individually, but rather are estimated as a group and reported as a single source category. The emission estimation technique used to develop the statewide HCHO emissions inventory for composite wood products required knowledge of two fundamental elements: (1) rates of HCHO emission from HWPW, PB, and MDF, and (2) the amount of composite wood panels in use in California (CARB, 2006c). Rates of HCHO emission were estimated from measured air concentrations (Myers, 1984; Myers and Nagaoka, 1981). For uncoated panels, decreases in HCHO emission over time were estimated in consideration of published emission decay studies (e.g., Zinn et al., 1990). Emissions of HCHO from uncoated panels were projected to occur over an 11-year time period when emission rates stabilize to about 2% of a newly manufactured panel. For coated panels, it was assumed that the initial rate of decrease in HCHO emission would be moderated by the coating, and that it would take longer for unbound HCHO in the panel to be released to air (i.e., 20-years). Estimates of the total amount of composite wood products in California that could potentially emit HCHO to air were developed from annual product summaries prepared by the USDA (e.g., Howard, 2004).

For 2002, total statewide HCHO emissions from PB, MDF, and HWPW were estimated to be about 450, 190, and 240 tons per year, respectively. Thus, the total amount of HCHO emissions from this area-wide source category was about 900 tons per year.

## **E. Natural Occurrences**

Formaldehyde occurs naturally in the environment and it is a product of many natural processes. The primary sources of release from natural sources include biomass combustion, such as forest and brush fires (Howard, 1989). Other natural sources of HCHO include animal wastes, microbial by-products of biological systems, and plant volatiles (USDHHS, 1999). Photochemical oxidation of naturally emitted hydrocarbon precursors also account for HCHO emissions (Zhang et al., 2004). In water, HCHO is also formed by the irradiation of humic substances by sunlight (Kieber et al., 1990; WHO, 2001).

Formaldehyde is present as a metabolic intermediate and exists at low levels in most living organisms (WHO, 2001). The basic pathway for cellular metabolism

of HCHO involves formic acid formation, catalyzed by formaldehyde dehydrogenase and glutathione, which is quickly removed by the supporting blood supply (Heck et al., 1982). The extent of exposure to HCHO other than by inhalation is very small under normal circumstances. In California, HCHO is present in drinking water in very low amounts. Except for accidental water contamination with HCHO, concentrations in drinking water are  $< 0.1$  mg/L (WHO, 2001). Formaldehyde levels in food are higher, but the majority of HCHO present in food is not absorbed; rather it is rapidly converted to harmless metabolites in the body (CARB, 1992). Fruits and vegetables typically contain 3 to 60 mg/kg, milk and milk products approximately 1 mg/kg, meat and fish 6 to 20 mg/kg, and shellfish 1 to 100 mg/kg (WHO, 2001).

Reaction of HCHO with primary and secondary amines, thiols, hydroxyls and amides to form methylol derivatives is virtually instantaneous (WHO, 2001). During chemical reactions, HCHO acts as an electrophile and reacts with macromolecules, such as proteins, DNA, and RNA to form reversible adducts or irreversible cross-links. When HCHO is absorbed it can be oxidized to formate (a salt or ester of formic acid) along three different pathways, and exhaled as carbon dioxide (USDHHS, 1999). In the human body, HCHO is produced in small quantities as a normal metabolite and as well as in the oxidative demethylation of xenobiotics (i.e., foreign materials to the body), thus it accumulates in the liver. Removal of HCHO from blood plasma occurs with a half-life of approximately 1 to 1.5 minutes, with most of it being converted to carbon dioxide and exhaled via the lungs. Smaller amounts of HCHO are excreted in urine as formate salts and several other metabolites (WHO, 2001).

## **F. Measured Formaldehyde Concentrations**

Formaldehyde concentrations range considerably depending on where measurements are made. This section provides an overview of measured and modeled concentrations in a range of microenvironments.

### **1. Outdoor Concentrations**

Formaldehyde is the most common aldehyde in the environment and it is usually present in the highest concentration of all the major aldehydes and ketones in ambient air (Finlayson-Pitts and Pitts, 2000). Since HCHO in outdoor air has the potential to enter buildings, schools, and residential areas, measured indoor concentrations must be gauged against outdoor levels of HCHO (3 to 4  $\mu\text{g}/\text{m}^3$ ; see Table III-5). The natural background concentration of HCHO is  $< 1$   $\mu\text{g}/\text{m}^3$  (1 ppb = 1.23  $\mu\text{g}/\text{m}^3$ ), with a mean = 0.5  $\mu\text{g}/\text{m}^3$  (IARC, 1995). Concentrations in unpopulated areas, rural-urban interfaces and large-urban areas are reported to range from 0.4 to 2.5, 0.1 to 12.3, and 1.2 to 73.8  $\mu\text{g}/\text{m}^3$ , respectively (Finlayson-Pitts and Pitts, 2000).

In late 1984, CARB established a statewide air toxic monitoring network to facilitate the identification of air toxics which pose an inhalation risk to the largest number of people in the state. Ambient levels of HCHO are routinely monitored in the CARB toxics network, and the data are used to support human exposure and health risk assessments, assess temporal trends, changes in the environmental quality, and impacts on the environment.

The CARB's HCHO sampling network encompasses 15 air basins across California, including the eight most populous, which reflect the highest priority locations in the state (Figure III-2 – labeled as Figure 10). The ambient monitoring network consists of 17 air monitoring stations, where 24-hour samples are collected on a one day in 12 day schedule. Formaldehyde is continuously extracted from ambient air to silica cartridges coated with acidified 2, 4-dinitrophenylhydrazine (DNPH) (CARB, 2001). An ozone scrubber is installed upstream from the sampling cartridge in order to eliminate interference by ozone. During sampling, HCHO reacts with DNPH to form hydrazone derivatives which are eluted from the cartridges and quantified by reverse-phase high performance liquid chromatography with ultraviolet absorption detector at 360 nm.

Outdoor HCHO concentrations were obtained from the Annual Statewide Toxics Summary (Table III-6) for 1996 through 2005 (CARB, 2006b). The mean ambient HCHO concentration was 3.69  $\mu\text{g}/\text{m}^3$  and the maximum was 18.45  $\mu\text{g}/\text{m}^3$ . Trends for California have shown a steady mean level for the past decade, with annual HCHO concentrations ranging from 3.14 to 4.31  $\mu\text{g}/\text{m}^3$ . The highest mean values measured were 4.23 and 4.31  $\mu\text{g}/\text{m}^3$  in 1996 and 2002, respectively. Minimum HCHO concentrations ranged from 0.06  $\mu\text{g}/\text{m}^3$  (recorded in multiple years) to 0.4  $\mu\text{g}/\text{m}^3$  in 2002. Maximum values ranged from 9.7  $\mu\text{g}/\text{m}^3$  in 2000 to 32.0  $\mu\text{g}/\text{m}^3$  in 2001. While maximum values have been fairly consistent in 2002-2005, minimum values are higher than in the late 1990's.

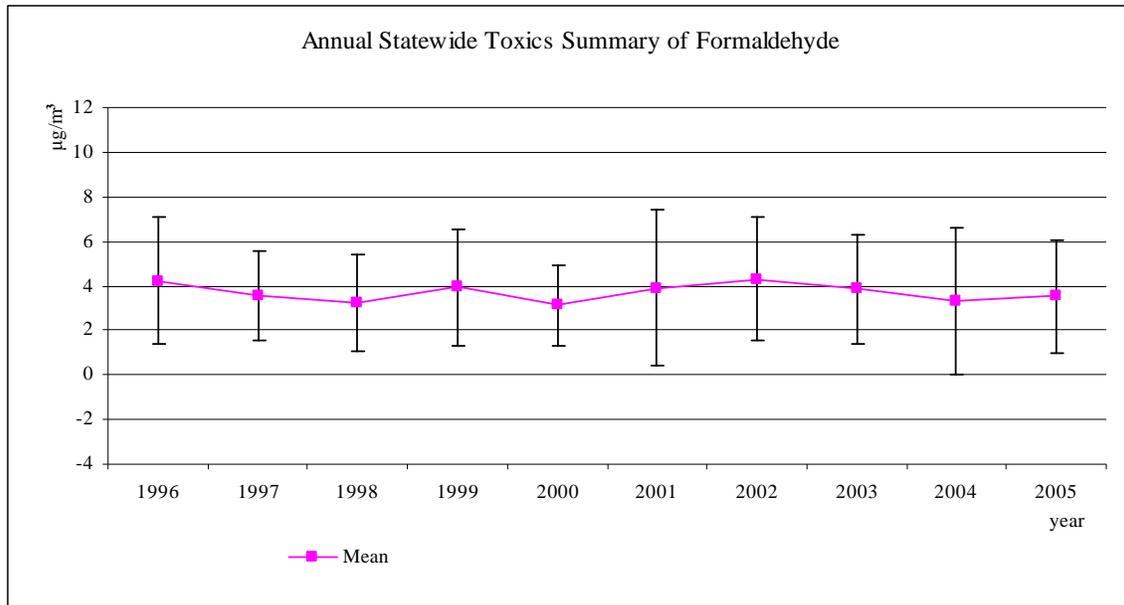
Table III-5. Statewide Annual Average Formaldehyde Concentrations ( $\mu\text{g}/\text{m}^3$ ): 1996-2005<sup>1</sup>

Year	Range	Mean ( $\pm$ SD)
2005	0.2 to 17.2	3.52 $\pm$ 2.52
2004	0.1 to 18.5	3.31 $\pm$ 2.35
2003	0.2 to 14.8	3.87 $\pm$ 2.46
2002	0.4 to 22.1	4.31 $\pm$ 2.80
2001	0.06 to 32.0	3.91 $\pm$ 3.51
2000	0.2 to 9.7	3.14 $\pm$ 1.82
1999	0.06 to 16.0	3.94 $\pm$ 2.61
1998	0.06 to 12.3	3.25 $\pm$ 2.19
1997	0.06 to 14.8	3.55 $\pm$ 2.03
1996	0.06 to 27.1	4.23 $\pm$ 2.85

<sup>(1)</sup> Source: CARB (2006b). " $\mu\text{g}/\text{m}^3$ " = micrograms per cubic meter; "SD" = standard deviation. Detection limit = 0.123  $\mu\text{g}/\text{m}^3$ .

The standard deviation in statewide annual average HCHO concentration has been fairly consistent from year-to-year (Figure III-1). The maximum standard deviation was recorded in 2001 ( $3.51 \mu\text{g}/\text{m}^3$ ) and the lowest in 2000 ( $1.82 \mu\text{g}/\text{m}^3$ ). This is consistent with our understanding of regional-scale ambient HCHO concentrations which are largely determined by rates of photochemical processes.

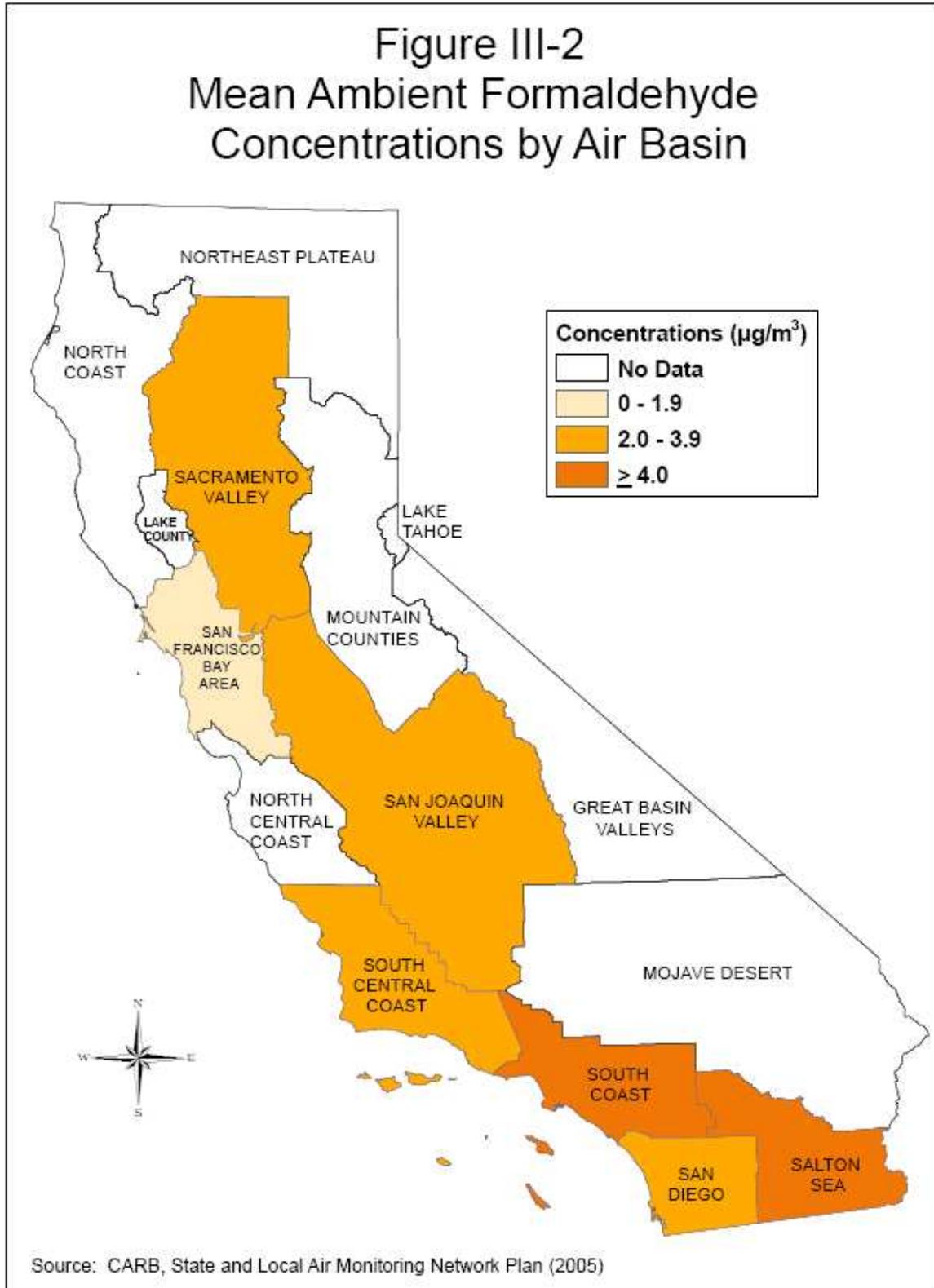
Figure III-1. Annual Statewide Summary for Ambient Formaldehyde<sup>1</sup>



<sup>(1)</sup> Source: CARB (2006b).

The statewide characterization of ambient HCHO in 2005-2006 was accomplished by measuring levels at selected locations across the state. Summary data for each of the monitoring sites is presented in Table III-7. These data were collected from January 2005 through April 2006; the most recent quality-assured data from the CARB network. Concentrations of HCHO varied across air basins, where in southern California, concentrations tended to be higher ( $\geq 4.0 \mu\text{g}/\text{m}^3$ ) than in northern California ( $< 3.0 \mu\text{g}/\text{m}^3$ ). Intermediate concentrations ( $2.0$  to  $2.9 \mu\text{g}/\text{m}^3$ ), were observed in inland basins, South Central Coast, and the San Diego Basin.

Figure III-2. Mean Ambient Formaldehyde Concentrations by Air Basin.



At individual monitoring sites, mean annual concentrations ranged from 1.3  $\mu\text{g}/\text{m}^3$  (San Francisco) to 7.5  $\mu\text{g}/\text{m}^3$  (Los Angeles) (Table III-6), while basin averages ranged from 1.6  $\mu\text{g}/\text{m}^3$  in San Francisco Bay Area to 4.6  $\mu\text{g}/\text{m}^3$  in the South Coast. The wide variation in HCHO concentration may have been due to a number of factors. Variations in ambient HCHO may be influenced by the number and types of sources located in a region, areas of heavy traffic, elements of climate, vegetation, varying terrain and geographical characteristics (near the coast versus inland), local meteorological patterns, and photochemical activity.

Table III-6. Summary of Ambient Formaldehyde Concentrations ( $\mu\text{g}/\text{m}^3$ ): 1 January 2005 through 30 April 2006 <sup>1</sup>		
Air Basin/Site Location	Range	Mean $\pm$ SD
A. Southern California		
South Coast Air Basin		
Azusa	0.5 to 8.4	4.1 $\pm$ 2.4
Burbank	0.5 to 9.1	4.9 $\pm$ 2.4
Los Angeles	2.5 to 17.2	7.5 $\pm$ 3.6
North Long Beach	0.5 to 7.5	3.1 $\pm$ 1.5
Riverside	0.9 to 8.0	3.6 $\pm$ 2.2
South Central Coast Air Basin		
Simi Valley	0.5 to 4.8	2.6 $\pm$ 1.6
San Diego Air Basin		
Chula Vista	0.5 to 5.0	2.4 $\pm$ 1.0
El Cajon	0.6 to 6.2	3.0 $\pm$ 1.4
Salton Sea Air Basin		
Calexico	0.5 to 12.5	4.0 $\pm$ 2.4
B. Northern California		
San Francisco Bay Area Air Basin		
Freemont	0.4 to 3.8	1.5 $\pm$ 0.9
San Francisco	0.4 to 3.1	1.3 $\pm$ 0.7
San Jose	0.5 to 5.2	2.0 $\pm$ 1.3
San Joaquin Valley Air Basin		
Bakersfield	0.6 to 6.5	2.9 $\pm$ 1.7
Fresno	0.9 to 8.5	3.3 $\pm$ 2.2
Stockton	0.5 to 4.6	2.1 $\pm$ 1.2
Sacramento Valley Air Basin		
Chico	0.4 to 12.3	3.5 $\pm$ 3.1
Roseville	0.7 to 5.9	2.3 $\pm$ 1.4
<sup>(1)</sup> Source: CARB (2006b).		

Table III-7 shows countywide HCHO emissions data (tons/year) from the 2005 emissions inventory. The high ambient HCHO levels in the South Coast Air Basin follow from the presence of four of the top ten HCHO emitting counties, particularly Los Angeles County (CARB, 2006a). The six other counties in the state's top ten accounted for approximately 25% of statewide HCHO emissions.

Table III-7. Formaldehyde Emissions in the Top Ten California Counties <sup>1</sup>			
County	Air Basin	Formaldehyde Emissions	
		Tons/Year	% of State
Los Angeles	South Coast	2,664	14
San Diego	San Diego	1,240	6
Kern	San Joaquin Valley	1,184	6
Orange	South Coast	908	5
Alameda	San Francisco Bay	711	4
Santa Clara	San Francisco Bay	647	3
Santa Barbara	South Central Coast	585	3
Fresno	San Joaquin	558	3
Riverside	South Coast	529	3
San Bernardino	South Coast	522	3

(<sup>1</sup>) Source: CARB (2006b).

Urban environments, such as Los Angeles (and large cities within other major air basins), commonly experience unhealthy air quality and high HCHO emissions. The most dominant source of HCHO in the troposphere is the oxidation of biogenic and anthropogenic hydrocarbons. Formaldehyde is also an important intermediate in the oxidation of hydrocarbons to carbon monoxide (CO); it is an ozone precursor and thus plays an important role in tropospheric ozone chemistry. Direct HCHO emissions also contribute to ambient HCHO, which are primarily derived from motor vehicles (CARB, 2006a). In future years, the adoption of increasingly stringent exhaust emission standards for motor vehicles will further reduce HCHO from this source category.

## **2. Indoor Concentrations**

Generally, indoor HCHO concentrations are several times higher, and sometimes one or two orders of magnitude higher, than levels in ambient air, due to a higher concentration of sources in a confined space with reduced air mixing. As discussed, the major sources of HCHO are composite wood products in structural or finished product applications, permanent press clothing, some consumer products, upholstery, combustion sources, and environmental tobacco smoke. Many factors influence indoor HCHO concentrations, among them are

the emission rate and pattern, age of the sources, the ratio of source surface area to the indoor air volume, the indoor-outdoor air exchange rate, humidity, and temperature. Mobile homes contain significant amounts of high-emitting materials in a relatively small air space, and newer homes generally have greater amounts of new building materials that have the highest HCHO emission rates.

Table III-8. Measured Indoor Formaldehyde Concentrations ( $\mu\text{g}/\text{m}^3$ ) <sup>1</sup>		
Environment	Average	Maximum
Manufactured Homes	46	279
Classrooms (Inside)	22	135
Conventional Homes	17	285
Office Buildings	16	32

(<sup>1</sup>) Source: CARB (2005b). "Average" or "Maximum" values are the average or maximum values calculated from the data or reported in the one to four studies referenced for each environment.

The current estimates of indoor HCHO levels in California span a broad spectrum of values. Estimates of average HCHO concentrations are useful in order to illustrate relative levels among the different environments, and to understand how Californian's exposures compare to health benchmarks. Manufactured homes have the highest estimated average HCHO levels of  $46 \mu\text{g}/\text{m}^3$  (CARB, 2005b, based on Sexton et al. (1986) and others). As manufacturing practices have changed since the early 1980's, HCHO emissions from new composite wood products are lower today than what they were, as evidenced by an average reduction of about 50% measured by Kelly et al. (1999) compared to Pickrell et al. (1983).

Data from the California Portable Classrooms Study collected in 2001 and 2002 were used to estimate school-year average and maximum HCHO concentrations. A large statewide data set was collected across four seasons using both active and passive sampling methods. The calculated school-year average HCHO concentration, including both warmer and cooler season values, was  $22 \mu\text{g}/\text{m}^3$  (CARB, 2005a). The statewide maximum mean was  $135 \mu\text{g}/\text{m}^3$ ; however, this value excluded extreme values measured in the study population. Results from the Portable Classrooms Study showed that HCHO concentrations in 4% of California's classrooms (i.e., 10,720 classrooms housing 200,000 to 300,000 children) exceeded OEHHA's 8 hour reference exposure level for acute eye, nose, and lung irritation, and all of the classrooms in the study exceeded a one in a million excess lifetime cancer risk level.

Estimates for current conventional home concentrations of HCHO were estimated from two studies from the 1990's (CARB, 2005b). In the National Human Exposure Assessment Survey (NHEXAS) conducted in 189 Arizona homes over several years, HCHO levels were measured using passive badges (Gordon et al., 1999). The NHEXAS utilized a probability-based sampling scheme to obtain data representative of the entire state. The second study, conducted in southern California, examined a population that resided in older homes in a mild climate (Avol, 1996). Results from the two studies were weighted by sample size to calculate estimates for conventional California homes. The estimated average HCHO concentration was 17  $\mu\text{g}/\text{m}^3$  and the maximum was 285  $\mu\text{g}/\text{m}^3$ .

The USEPA Building Assessment Survey and Evaluation (BASE) study, conducted in 100 large office buildings across the country from 1994 to 1998, found that pollutant levels in office buildings, including HCHO, were variable. The average and 95<sup>th</sup> percentile levels for HCHO were 16 and 32  $\mu\text{g}/\text{m}^3$  (USEPA, 2007).

All of these studies reflect the continuously elevated exposures that Californians experience throughout their day. Concentrations in all of these major indoor environments exceed acceptable health benchmarks for excess cancer risk, and even those for prevention of acute impacts.

a. Portion of Formaldehyde Emitted Indoors that Moves Outdoors

Nearly all HCHO directly emitted indoors from indoor sources moves to the outdoors. Most such indoor-emitted HCHO moves outdoors within hours, primarily through indoor-outdoor air exchange from mechanical and natural ventilation and building leakage. Some HCHO is reversibly sorbed onto surfaces in the indoor space at a rate dependent on the indoor air concentration (vapor pressure) of HCHO, the actual surface area of the indoor surfaces, air movement, and other factors, with subsequent desorption at a future time. A small portion may be irreversibly lost through oxidative decomposition and other processes when uptake occurs in a surface water film, but this has not been quantified. A very low percentage of HCHO – from < 1% up to 7%, depending on the air exchange rate and other factors – is estimated to be removed through homogeneous chemical reactions that result in permanent removal of HCHO. Thus, a conservative estimate for the portion of HCHO emitted indoors that eventually makes its way outdoors is 90 to 100%, with the vast majority of the HCHO moving outdoors within hours of being released indoors.

i. Release to the Outdoors through Air Exchange

Formaldehyde is a very volatile chemical that is readily transported to the outdoors as indoor air is replaced by outdoor air. All indoor spaces exchange air with the outdoors through mechanical or natural ventilation, or both, as well as

through infiltration due to building leakage, such as through construction interfaces and utility penetrations. Most homes in California are ventilated by infiltration and through opening of windows and doors (natural ventilation). A small percent of newly constructed homes have mechanical ventilation systems that actively draw outdoor air into the indoor space. Most medium and large public and commercial buildings are mechanically ventilated with a system that moves large quantities of air through the building over time in order to meet building ventilation requirements. Smaller public and commercial buildings are more variable in the type of ventilation they use; some have small mechanical systems that actively exchange air, while others are more similar to residential buildings and rely on natural ventilation and leakage for air exchange. Consequently, public and commercial buildings have a more variable range of air exchange rates than residences.

The air exchange rate (AER) of a building is typically expressed as the number of building volumes of air that enter each hour, also called air changes per hour. Due to airflow patterns, incomplete mixing of air in some indoor spaces, and non-uniform distribution of indoor pollutant sources, ventilation efficiency is typically less than 100%. Ventilation efficiency generally refers to the effectiveness of the ventilation system or conditions in reducing such aspects as air pollutant concentrations, odors, and excessive heat, relative to the feasible theoretical maximum reduction (Bearg, 1993). In indoor spaces with reasonably well-mixed air, the decrease in the concentration of an indoor contaminant can be expressed based on the time constant of the ventilation process, or  $1/N$  (in units of hours), where  $N$  is the air exchange rate (Bearg, 1993; Maroni et al., 1995). For an AER of 0.5 per hour, then,  $1/N = 1/0.5 = 2$  hours. After one time constant, or 2 hours, 63% of the original body of indoor air would be released outdoors, based on an exponential decay function, and 37% would remain; after two time constants (4 hours in this example) only 13.5% of the original body of air would remain.

Air exchange rates (AERs) in California homes range from about 0.10 to 3.0 air changes per hour, averaging about 0.5 to 1 in the winter, and about 1 to 3 in the summer (Ozkaynak et al., 1996; Sheldon et al., 1993; Wilson et al., 1993; Berkeley Solar Group and Xenergy, 1990; Pellizzari et al., 1989; Wilson et al., 1986; Koontz 1998; Pandian et al., 1993, 1998). In light of the various improvements in energy efficiency in California homes required through regulation or encouraged through rebates and other utility programs over the past decade, current average air exchange rates are likely closer to the lower ends of these ranges, or about 0.5 AER in the winter and 1 to 1.5 in the summer. Thus, based on the discussion above, the volume of air indoors is moved to the outdoors within a matter of hours under typical residential conditions. This several hour residence time of HCHO indoors may allow the opportunity for permanent loss of a very small portion of the HCHO through chemical reaction and some temporary loss through sorption onto surfaces (discussed below). However, most of the HCHO emitted indoors would be lost to the outdoors within several hours due to the exchange with outdoor air.

Air exchange rates in public and commercial buildings range from about 0.2 to 9, averaging about 1 to 2.5 (Grot, 1995; Persily, 1989; Turk et al., 1987). Based on the time constant discussion above, the volume of air in these buildings would typically be replaced within a few hours. Thus, with the exception of areas of poor air mixing in the building, nearly all of the HCHO in a building at a given point in time would be expected to be moved to the outdoors within several hours.

## ii. Sorption to Indoor Surfaces and Materials

Like other VOCs, HCHO displays sorption to and subsequent desorption from indoor materials (sink effects) such as carpet, walls, and furnishings. The rates of sorption and desorption are dependent on the air concentration (vapor pressure) in the room, temperature and humidity, the actual surface area ("fleece factor" – accounting for roughness and porosity), the indoor-outdoor air exchange rate and the efficiency of air mixing, and characteristics of the pollutant and the specific surface material (Weschler, 2003; Zhang et al., 2002; Won et al., 2001; Van der Wal et al., 1997; Tichenor et al., 1991; Nazaroff and Cass, 1989).

However, sorption has generally been found to result in little or no permanent loss of HCHO and other very volatile compounds. Matthews et al. (1987) found that common gypsum board used for interior walls sorbed and released HCHO based on its vapor concentration in the air surrounding the board, with sorption highest with high air concentrations and desorption highest with low air concentrations, and very little loss of HCHO. In a study of ventilation and VOC concentrations in a call center, Hodgson et al. (2003) found that emissions of HCHO were elevated at higher ventilation rate conditions; the authors speculated that this association was attributable to re-emission from the indoor material sinks. Smedje and Norback (2001) found that after adjusting for season and air exchange rate, an increase in fleece factor of  $0.1 \text{ m}^2/\text{m}^3$  was associated with an increase in HCHO of  $4 \text{ }\mu\text{g}/\text{m}^3$ , and they concluded that furnishings and textiles acted as significant pollutant reservoirs in the classrooms studied. Van der Wal et al. (1998) did not test HCHO but found that other very volatile compounds exhibited a weak sorption effect, even when tested with the strongest sink (woollen carpet).

Based on formaldehyde's hydrophilic nature and possible reactivity with amino groups, a small portion of indoor-emitted HCHO may be permanently lost through oxidative decomposition and other processes when uptake occurs in a surface water film, but this has not been quantified. The limited data on HCHO to date generally indicate higher levels of HCHO associated with increased ventilation rates, which is consistent with substantial re-emission of HCHO from indoor sinks.

### iii. Estimated Reactivity Losses

Indoor HCHO reactions appear to differ from those outdoors. The half-life of HCHO in the outdoor environment is estimated to range from about 4 to 10 hours (Kao, 1994; Atkinson, 1990). However, this relatively short lifespan is largely attributable to photolysis, which generally does not occur in indoor environments (or is very much reduced) due to lack of sunlight, and to reactions with atmospheric chemical species not normally present in large quantities indoors.

Indoor reactivity loss of HCHO is believed to be largely attributable to homogeneous decomposition dominated by attack by the hydroxyl (OH) radical (Weschler and Shields 1996; Nazaroff, 2006). Ozone/alkene reactions can produce hydroxyl radicals indoors, resulting in "typical" OH levels indoors estimated at about  $7 \times 10^5$  molecules/cm<sup>3</sup> (or  $2.8 \times 10^{-5}$  ppb) by Weschler and Shields (1997). The reaction of hydroxyl with HCHO has a second order rate constant of 0.24 per ppb per second, or 860 per ppb per hour (Weschler and Shields, 1996). From this information, Nazaroff (2006) has estimated a first order loss rate coefficient of 0.024 per hour (R), and a fractional degree of reduction in the indoor concentration of HCHO from homogeneous chemical reaction equal to approximately  $1 - [A/(A + R)]$ , where A equals the AER. Thus, for an AER of 0.5, the HCHO concentration would be reduced by  $1 - [(0.5)/(0.5 + 0.024)]$ , or about 5%. For an air exchange rate of 3 it would be reduced by about 0.8%, and for an AER of 0.3, it would be reduced by about 7.4%. These results are consistent with Weschler and Shields (2000) who found that concentrations of products generated from reactions among indoor pollutants increased as ventilation rates decreased. Thus, permanent loss due to reaction indoors might range from less than 1% up to 7%. However, because most buildings experience AERs of 0.5 and higher, the percent reduction in HCHO levels would generally be very low, less than 5%.

Few other indoor HCHO reactions have been reported or studied. Formaldehyde loss from reaction with ozone indoors has been found to be negligible, due to the exceedingly low rate constant of this reaction (Weschler 2000). Other reactions likely occur, but at levels too low to be readily evident. Consequently, reactivity losses indoors are estimated to total 1 to 7% of HCHO, but typically less than 5%, and total permanent loss of HCHO indoors due to any cause is estimated conservatively at no more than 10% total.

### **3. In-vehicle Concentrations**

Pollutant concentrations were measured in-vehicles in simulated two-hour commutes in Los Angeles and Sacramento (Research Triangle Institute, 1998). The measured pollutants included particulate matter, metals, and selected organic compounds, including HCHO. In-vehicle HCHO levels were generally higher in Los Angeles than in Sacramento, where average in-vehicle concentrations ranged from 10 to 22  $\mu\text{g}/\text{m}^3$  and 5 to 14  $\mu\text{g}/\text{m}^3$ , respectively. In

two “maximum concentration” commutes designed to achieve the highest in-vehicle pollutant concentration possible, concentrations of 62 to 68  $\mu\text{g}/\text{m}^3$  were recorded. Compared to concentrations at roadside or ambient air monitoring stations (i.e., 2 to 4  $\mu\text{g}/\text{m}^3$  in Sacramento and 7 to 19  $\mu\text{g}/\text{m}^3$  in Los Angeles), average in-vehicle HCHO levels were typically two to four times higher. While factors such as roadway condition, congestion level, and time-of-day were found to variably influence in-vehicle pollutant levels, the effects of vehicle type and ventilation settings were found to be minimal.

## **G. Modeled Formaldehyde Concentrations**

A near-source air dispersion modeling approach was used to estimate HCHO concentrations in outdoor air in two scenarios. This section describes the HCHO concentrations that may result near a warehouse store or downwind of a PB plant and associated cancer risks.

### **1. Near-source Modeling**

Near-source air dispersion modeling was conducted to estimate the outdoor air concentrations of HCHO resulting from emissions of HCHO from composite wood products. Two scenarios were modeled: (1) a warehouse-size home repair store with a large amount of composite wood products stored inside, with emissions exiting the building through a large roll-up door, and (2) bundles of particleboard stacked outdoors under a pole barn. In both scenarios, the nearest receptor, a resident, was assumed to be located approximately 30 meters from the point of emissions. Emissions were estimated for the different types of composite wood products based on emission factors summarized in Appendix C that are based on studies conducted by Battelle (1996). The USEPA Industrial Source Complex Short Term (ISCST3) air dispersion model was used to model HCHO concentrations downwind of the sites (USEPA, 1995). Because meteorological conditions vary throughout California, meteorological data from the following five cities were used: Burbank, Fresno, Oakland, Pasadena, and San Diego. An annual average air concentration was estimated for both scenarios at a distance of 30 meters from the emission source. The results of the modeling are contained in Appendix C.

Cancer risk estimates can be calculated by using modeling results and the cancer unit risk factor for HCHO developed by the Office of Environmental Health Hazard Assessment (OEHHA, 2005) of  $6.0 \times 10^{-6}$  per  $\mu\text{g}/\text{m}^3$ . The modeled annual average HCHO concentration for both scenarios corresponded to a cancer risk ranging from about 0.1 to 0.3 excess cancer cases per million people exposed, assuming a 70-year lifetime exposure. This modeling analysis demonstrates that composite wood products contribute to outdoor cancer risk.

## **2. Near-source Modeling of a Particleboard Plant**

Similar to the near-source modeling described in subsection III.G. above, worst-case assumptions were made about what near-source HCHO concentrations could be downwind of a particleboard manufacturing plant. The Occupational Safety & Health Administration's (OSHA) permissible 8-hour exposure level for HCHO is  $937.5 \mu\text{g}/\text{m}^3$  (0.75 ppm) (OSHA, Not Dated). This concentration was assumed to be uniform throughout a large manufacturing plant of 100 meters by 100 meters with a 5 meter high ceiling. The following calculation was used to estimate an emission rate:

$$\frac{(937.5 \mu\text{g}/\text{m}^3)(100 \text{ m})(100 \text{ m})(5 \text{ m})}{(8 \text{ hr})} = 5.86 \times 10^6 \mu\text{g}/\text{hr}$$

This emission rate is 42-times higher than in the warehouse-size home repair store scenario described in subsection III.G.1. In air dispersion modeling, downwind concentrations are directly proportional to the emission rate. Hence, the downwind air concentration could be as high as 42 times higher than downwind of the warehouse-size home repair store, or as high as  $0.0225 \mu\text{g}/\text{m}^3 \times 42$ , for an estimated annual average concentration of  $0.94 \mu\text{g}/\text{m}^3$ . This corresponds to a risk of about six excess cancer cases per million people exposed, assuming a 70-year lifetime exposure.

### **H. Atmospheric Persistence**

Formaldehyde can be present in the atmosphere in two ways: it can be directly emitted into the atmosphere or it can be formed in the atmosphere from methane and non-methane hydrocarbons through photochemical degradation. In California, photochemical degradation is the largest source of HCHO in ambient air (CARB, 2006a). The dominant atmospheric removal process for HCHO in the lower troposphere occurs primarily by photolysis and oxidation by hydroxyl radicals and by wet deposition, which leads to the incorporation of HCHO into the rain, cloud and fog water (CARB, 1992). In the absence of nitrogen dioxide, the half-life of HCHO is estimated to be 50 minutes during the daytime, but only 35 minutes when nitrogen dioxide is present (Bufalini et al., 1972). With photolysis as the principal removal mechanism, atmospheric lifetimes of approximately 7 and 4 to 10 hours, were calculated by Atkinson (1990) and Kao (1994), respectively. Episodic removal by wet deposition (e.g., rain, snow, or fog) can also occur, resulting in shorter atmospheric lifetimes on an event-basis.

### **I. Risk Characterization**

A "toxic air contaminant" is defined in H&SC §39655(a) as:

"...an air pollutant which may cause or contribute to an increase in mortality or in serious illness, or which may pose a present or potential hazard to human health."

Presently, there are approximately 200 compounds that have been designated as top ten TACs in California (CARB, 1999), and HCHO is one of the most harmful TACs based on its potential public health risk (CARB, 2006a). In terms of estimated chances per million of developing cancer over a 70-year lifetime (i.e., 20 chances per million), exposure to ambient annual average concentrations of HCHO rank third behind diesel particulate matter (540 chances per million) and benzene (43 chances per million). While statewide efforts to control mobile source exhaust emissions have led to major reductions in emissions of diesel particulate matter, benzene, and HCHO, efforts to reduce other sources of HCHO have been limited.

Studies show that Californians spend close to 90% of the day indoors (University of California, Berkeley, 1991), where HCHO concentrations are reported to be four- to ten-times higher than outdoors (CARB, 2005b). Estimates of the lifetime cancer risk from total daily exposure to HCHO are provided in section VII.D.

## **J. References**

Atkinson R. 1990. Lifetimes and Fates of Toxic Air Contaminants in California's Atmosphere. Appendix E: Atmospheric Lifetime and Fate of Formaldehyde. Final Report, CARB Contract No. A732-107, Research Division, Sacramento, CA. 28 pp.

Avol E. 1996. Residential Microenvironmental and Personal Sampling Project for Exposure Classification. Final Report, CARB Contract No. 92-317, Research Division, Sacramento, CA.

Battelle. (1996). Determination of Formaldehyde and Toluene Diisocyanate Emissions from Indoor Residential Sources. Final Report, CARB Contract No. 93-315, Research Division, Sacramento, CA.

Bearg DW. 1993. Ventilation Characterization. In: Indoor Air Quality and HVAC Systems. Lewis Publishers, CRC Press, Boca Raton, FL. Chapter 7, p. 125-142.

Berkeley Solar Group and Xenergy. 1990. Occupancy Patterns and Energy Consumption in New California Houses (1984-1988). California Energy Commission Consultant Report, P400-90-009, Sacramento, CA.

Bufalini JJ, BW Gay Jr, and KL Brubaker. 1972. Hydrogen peroxide permeation from formaldehyde photooxidation and its presence in urban atmospheres. *Environmental Science & Technology*, 6(9): 816-821.

California Air Resources Board (CARB). 1992. Identification of Formaldehyde as a Toxic Air Contaminant. Part A. Exposure Assessment. Technical Support Document, Stationary Source Division, Sacramento, CA. 103 pp.

CARB. 1999. Update to the Toxic Air Contaminant List. Staff Report, Stationary Source Division, Sacramento, CA. 23 pp.

CARB. 2001. Standard Operating Procedure for the Determination of Carbonyl Compounds in Ambient Air. SOP MLD 022. Northern Laboratory Branch, Monitoring and Laboratory Division, Sacramento, CA. 10 pp.

CARB. 2004. More information on areawide source categories. From: <http://www.arb.ca.gov/ei/areasrc/moreareainfo.htm> Accessed: 13 February 2007.

CARB. 2005a. State and Local Air Monitoring Network Plan. From: <http://www.arb.ca.gov/aqd/namslams/namslams.htm> Accessed: 10 October 2006.

CARB. 2005b. Indoor Air Pollution in California. Report to the Legislature, Pursuant to Health & Safety Code §39930. Research Division, Sacramento, CA. 248 pp (plus appendices).

CARB. 2006a. The California Almanac of Emissions and Air Quality, 2006. Planning & Technical Support Division, Sacramento, CA. 506 pp.

CARB. 2006b. Annual Statewide Toxics Summary. Accessed: 14 October 2006. From: <http://www.arb.ca.gov/adam/toxics/statepages/hchostate.html>

CARB. 2006c. Estimation of 2002 Formaldehyde Emission Inventory from Composite Wood Products. Planning & Technical Support Division, Sacramento, CA. 30 pp.

Canadian Centre for Occupational Health and Safety. 2005. Formaldehyde gas. Cheminfo. Accessed: 11 May 2006. From: <http://intox.org/databank/documents/chemical/formalde/cie422.htm>

Finlayson-Pitts BJ and JN Pitts Jr. 2000. Chemistry of the Upper and Lower Atmosphere: Theory, Experiments, and Applications. Academic Press, San Diego. 969 pp. [QC879.6 F5]

The Formaldehyde Council, Inc. 2005. Formaldehyde: A Brief History and Its Contributions to Society and the U.S. and Canadian Economics. From: <http://formaldehyde.org/EconomicBackground.pdf> Accessed: 8 February 2007.

Gammage R and K Gupta. 1984. Formaldehyde. In: Walsh PJ CS Dudney and ED Copenhaver. Indoor Air Quality, p. 109-142. CRC Press, Boca Raton, FL.

Gerberich HR and GC Seaman. 1994. Formaldehyde. Kirk-Othmer Encyclopedia of Chemical Technology, 4<sup>th</sup> edition, p. 929-951.

Global Insight, Inc. 2006. Economic Primer on Formaldehyde. From: [http://www.formaldehyde.org/pdfs/GIEconomic Primer-04-20-06.pdf](http://www.formaldehyde.org/pdfs/GIEconomic%20Primer-04-20-06.pdf)  
Accessed: 24 May 2006.

Gordon SM, PJ Callahan, MG Nishioka, MC Brinkman, MK O'Rourke, MD Lebowitz, DJ Moschandreas. 1999. Residential environmental measurements in the National Human Exposure Assessment Survey (NHEXAS) pilot study in Arizona: Preliminary results for pesticides and VOCs. Journal of Exposure Analysis and Environmental Epidemiology, 9: 456-470.

Grot RA. 1995. Air Change Rates in Non-residential Buildings in California, California Energy Commission, Consultant Report P400-91-034BCN.

Heck Hd'A, EL White and M Casanova-Schmitz. 1982. Determination of formaldehyde in biological tissues by gas chromatography/mass spectrometry. Biomedical Mass Spectrometry, 9: 347-353.

Hodgson AT, D Faulkner, DP Sullivan, DL DiBartolomeo, ML Russell and WJ Fisk. 2003. Effect of outside air ventilation rate on volatile organic compound concentrations in a call center. Atmospheric Environment, 37(39-40): 5517-5527.

Howard JL. 2004. U.S. Forest Products Annual Market Review and Prospects: 2001-2004. Research Note, FPL-RN-0292. USDA, Forest Service, Forest Products Laboratory, Madison, WI. 9 pp.

Howard PH. 1989. Formaldehyde. In: Syracuse Research Corporation. Handbook of Environmental Fate and Exposure Data for Organic Chemicals. Volume I. Large Production and Priority Pollutants, p. 101-106. Lewis Publishers, Chelsea, MI.

International Agency for Research Cancer (IARC). 1995. Formaldehyde. In: Wood Dust and Formaldehyde. IARC Monographs on the Evaluation of the Carcinogenic Risk of Chemicals to Humans, 62: 21-362.

Kao AS. 1994. Formation and removal reactions of hazardous air pollutants. Journal of the Air and Waste Management Association, 44(5): 683-696.

Kelly TJ, DL Smith, and J Satola. 1999. Emission rates of formaldehyde from materials and consumer products found in California homes. Environmental Science & Technology, 33(1): 81-88.

Kieber RJ, Zhou X, Mopper K. 1990. Formation of carbonyl compounds from UV-induced photodegradation of humic substances in natural waters: Fate of riverine carbon in the sea. *Limnology and Oceanography*, 35(7): 1503–1515.

Koontz, MD, WC Evans and CR Wilkes. 1998. Development of a Model for Assessing Indoor Exposure to Air Pollutants. Final Report, CARB Contract No. A933-157, Research Division, Sacramento, CA.

Lide DR. 1999. Handbook of Chemistry and Physics. Chapman and Hall/CRCnetBase.

Liteplo RG, R Beauchamp, ME Meek, and R Chenier. 2002. Formaldehyde. Concise International Chemical Assessment Document 40. Accessed: 19 May 2006. From: <http://www.formaldehyde.org/WHO.pdf>

Maroni M, B Siefert and T Lindvall (eds). 1995. Indoor Air Quality: A Comprehensive Reference Book. Section 31.6.6, Ventilation effectiveness. Elsevier, Amsterdam, The Netherlands.

Matthews TG, AR Hawthorne, and CV Thompson. 1987. Formaldehyde sorption and desorption characteristics of gypsum wallboard. *Environmental Science & Technology*, 21(7): 629-634.

Meek ME, A Atkinson, and J Sitwell. 1985. Background paper on formaldehyde prepared for WHO working group on indoor air quality: Radon and formaldehyde. Bureau of Chemical Hazards, Health Protection Branch, Health and Welfare Canada, Ottawa. p. 1-124.

Merck Research Laboratories. 1989. 4148. Formaldehyde. In: Budavari S (ed). The Merck Index, Eleventh edition. Merck & Co., Inc. Rahway, New Jersey. 1606 pp.

Meyer B and K Hermanns. 1985. Formaldehyde release from pressed wood products. In: V Turoski (ed). Formaldehyde-analytical Chemistry and Toxicology. *Advances in Chemistry Series*, 210: 101-116.

Myers GE. 1984. Effect of ventilation rate and board loading on formaldehyde concentration: A critical review of the literature. *Forest Products Journal*, 34(10): 59-68.

Myers GE and M Nagaoka. 1981. Emission of formaldehyde by particleboard: Effect of ventilation rate and loading on air-contamination levels. *Forest Products Journal*, 31(7): 39-44.

National Cancer Institute. 2004 Formaldehyde and Cancer: Questions and Answers. Accessed: 3 March 2007. From: <http://www.cancer.gov/cancertopics/factsheet/Risk/formaldehyde>

Nazaroff WW. 2006. Personal communication to Peggy Jenkins, California Air Resources Board, June 22, 2006 and subsequent.

Nazaroff, WW and GR Cass. 1989. Mass-transport aspects of pollutant removal at indoor surfaces. *Environment International*, 15: 567-584.

Occupational Safety and Health Administration (OSHA). Not Dated. Formaldehyde – 1910.1048. Accessed: 28 February 2007. From: [http://www.osha.gov/pls/oshaweb/owadisp.show\\_document?p\\_table=STANDARDS&p\\_id=10075](http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=10075)

OEHHA. 2005a. Air Toxics Hot Spots Program Risk Assessment Guidelines. Part II. Technical Support Document for Describing Available Cancer Potency Factors. OEHHA, Sacramento, CA.

OEHHA. 2005b. Chronic Toxicity Summary: Formaldehyde. Accessed: 3 March 2007. From: [http://www.oehha.ca.gov/air/chronic\\_rels/pdf/50000.pdf](http://www.oehha.ca.gov/air/chronic_rels/pdf/50000.pdf)

Ozkaynak, H, J Xue, J Spengler, L Wallace, E Pellizzari, and P Jenkins. 1996. Personal exposure to airborne particles and metals: Results from the Particle TEAM Study in Riverside, California. *Journal of Exposure Analysis and Environmental Epidemiology*, 6(1): 57-78.

Pandian MD, JV Behar, WR Ott, LA Wallace, AL Wilson, SD Colome, and M Koontz. 1998. Correcting errors in the nationwide database of residential air change rates. *Journal of Exposure Analysis and Environmental Epidemiology*, (8)4: 577-586.

Pandian MD, WR Ott, and JV Behar. 1993. Residential air change rates for use in indoor air and exposure modeling studies. *Journal of Exposure Analysis and Environmental Epidemiology*, 3(4): 407-416.

Pellizzari, ED, LC Michael, K Perritt, DJ Smith, TD Hartwell and J Sebestik. , 1989. Development and Implementation of Exposure Assessment Procedures for Toxic Air Pollutants in Several Los Angeles County, California Communities. Final Report, CARB Contract No. A5-174-33, Research Division, Sacramento, CA.

Persily A. 1989. Ventilation rates in office buildings. In: *The Human Equation: Health and Comfort*. Proceedings of the ASHRAE/SOEH Conference, IAQ 89. April 17-20, 1989, San Diego, CA, p. 128-136.

Pickrell JA, BV Molder, LC Griffis, CH Hobbs, and A Bathija. 1983. Formaldehyde release rate coefficients from selected consumer products. *Environmental Science & Technology*, 17: 753-757.

Research Triangle Institute (RTI). 1998. Concentrations of Selected Air Pollutants Inside California Vehicles. Final Report, CARB Contract No. 95-339, Research Division, Sacramento, CA. 155 pp.

Reuss G, W Disteldorf, AO Gamer and A Hilt. 1988. Formaldehyde. In: Ullmann's Encyclopedia of Industrial Chemistry, 5<sup>th</sup> Edition, A11. VCH Publishers. p. 619-651.

Sax NI and RJ Lewis. 1989. Dangerous Properties of Industrial Materials, 7<sup>th</sup> Edition. Volumes 1-3. Van Nostrand Reinhold, New York.

Seyfioglu R and M Odabasi, 2006. Investigation of air-water exchange of formaldehyde using the water surface sampler: Flux enhancement due to chemical reaction, *Atmos. Environment* 40: 3503-3512.

Sexton K, K Liu, and M Petreas. 1986. Formaldehyde concentrations inside private residences: A mail-out approach to indoor air monitoring. *Journal of the Air Pollution Control Association*, 36: 698-704.

Sexton K, MX Petreas, and KS Liu. 1989. Formaldehyde exposures inside mobile homes. *Environmental Science & Technology*, 23(8): 985-988.

Sheldon L, A Clayton, J Keever, R Perritt and D Whitaker. 1993. Indoor Concentrations of Polycyclic Aromatic Hydrocarbons in California Residences. Draft Final Report, CARB Contract No. A033-132, Research Division, Sacramento, CA.

Smedje G and D Norbäck. 2001. Irritants and allergens at school in relation to furnishings and cleaning. *Indoor Air*, 11: 127-133.

Sterling TD, CW Collett, and EM Sterling. 1987. Environmental tobacco smoke and indoor air quality in modern office work environments. *Journal of Occupational Medicine*, 29: 57-61.

Syracuse Research Corporation. 2004. Environmental Fate Database: Chemfate Chemical Search. Accessed: 22 May, 2006. From: <http://www.syrres.com/esc/chemfate.htm>

Tichenor BA, Z Guo, JE Dunn, LE Sparks, and MA Mason. 1991. The interaction of vapour phase organic compounds with indoor sinks. *Indoor Air*, 1(1): 23-35.

Turk BH, JT Brown, K Geisling-Sobotka, DA Froehlich, DT Grimsrud, J Harrison, JF Koonce, RJ Prill and KL Revzan. 1987. Indoor Air Quality and Ventilation Measurements in 38 Pacific Northwest Commercial Buildings. Volume 1, LBL-22315 ½, Lawrence Berkeley Laboratory.

U.S. Department of Health & Human Services (USDHHS). 1999. Toxicological Profile for Formaldehyde. Public Health Service. Agency for Toxic Substances and Disease Registry. 423 pp.

USEPA. 1987. Assessment of Health Risks to Garment Workers and Certain Home Residents from Exposure to Formaldehyde. USEPA, Office of Pesticides and Toxic Substances.

USEPA. 1995. User's Guide for the Industrial Source Complex (ISC3) Dispersion Models. Volume I – User Instructions. Document No. EPA-454/B-95-003a, Office of Air Quality Planning and Standards, Research Triangle Park, NC. From: <http://www.epa.gov/scram001/userg/regmod/isc3v1.pdf>

USEPA. 2007. Volatile organic compounds master list. Accessed: 3 March 2007. From: [http://www.epa.gov/iaq/base/voc\\_master\\_list.html](http://www.epa.gov/iaq/base/voc_master_list.html)

University of California, Berkeley. 1991. Activity Patterns of California Residents. Final Report, CARB Contract No. A6-177-33, Research Division, Sacramento, CA. 63 pp.

Van der Wal JF, AW Hoogeveen, and L van Leeuwen. 1998. A quick screening method for sorption effects of volatile organic compounds in indoor materials. Indoor Air, 8: 103-112.

Van der Wal JF, AW Hoogeveen, and P Wouda. 1997. The Influence of temperature on the emission of volatile organic compounds from PVC flooring, carpet, and paint. Indoor Air, 7: 215-221.

Wade LG. 1999. Organic Chemistry. Prentice-Hall Publishing, 4<sup>th</sup> Edition. Whitman College. 1221 pp.

Walker JF. 1964. Formaldehyde, 3<sup>rd</sup> Edition. American Chemical Society Monograph Series. Reinhold Publishing Corporation. 701 pp.

Weschler CJ. 2000. Ozone in indoor environments: Concentration and chemistry. Indoor Air, 10: 269-288.

Weschler CJ. 2003. Indoor/outdoor connections exemplified by processes that depend on an organic compound's saturation vapor pressure. Atmospheric Environment, 37(39-40): 5455-5465.

Weschler CJ and HC Shields. 1996. Production of the hydroxyl radical in indoor air. *Environmental Science & Technology*, 30: 3250-3258.

Weschler CJ and HC Shields. 1997. Measurements of the hydroxyl radical in a manipulated but realistic indoor environment. *Environmental Science & Technology*, 37: 3719-3722.

Weschler CJ and HC Shields. 2000. The influence of ventilation on reactions among indoor pollutants: Modeling and experimental observations. *Indoor Air*, 10: 92-100.

Wilson AL, SD Colome, PE Baker and EW Becker. 1986. Residential Indoor Air Quality Characterization Study of Nitrogen Dioxide. Phase I Final Report for Southern California Gas Company.

Wilson AL, SD Colome and Y Tian. 1993. California Residential Indoor Air Quality Study, Volume 1: Methodology and Descriptive Statistics. Prepared for Gas Research Institute, Pacific Gas and Electric Company and Southern California Gas Company by Integrated Environmental Services, Irvine, CA.

Won D, RL Corsi, and M Rynes. 2001. Sorptive interactions between VOCs and indoor materials. *Indoor Air*, 11: 246-256.

World Health Organization (WHO). 2001. Formaldehyde. *Air Quality Guidelines*. Second Edition. Regional Office for Europe. Copenhagen, Denmark. Available: [http://www.euro.who.int/document/aig/5\\_8formaldehyde.pdf](http://www.euro.who.int/document/aig/5_8formaldehyde.pdf). Accessed: 8 February, 2007.

Zhang J, Q He, and PJ Liou. 1994. Characteristics of Aldehydes: Concentrations, Sources, and Exposures for Indoor and Outdoor Residential Microenvironments. *Environmental Science & Technology*, 28(1): 146-152.

Zhang J, J Zhang, Q Chen, and X Yang. 2002. A critical review on studies of volatile organic compound (VOC) sorption by building materials. No. RP-1097. *ASHRAE Transactions*, 108(1): 162-174.

Zinn T, WD Cline, and WF Lehmann. 1990. Long-term study of formaldehyde emission decay from particleboard. *Forest Products Journal*, 40(6): 15-18.

## IV. Manufacturing of Composite Wood Products

This chapter describes how the composite wood products subject to this ATCM are manufactured and the fundamental chemistry of commonly used formaldehyde-containing and no added HCHO resins (see Chapter V for details).

### A. Background

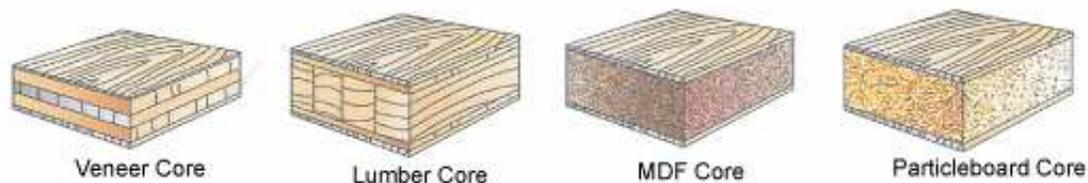
Hardwood plywood is made by gluing together hardwood plies, and used to make paneling, flooring, cabinets and furniture. Particleboard is made of wood fragments or particles glued together, and used to make countertops, cabinets, and floor underlayments. Medium density fiberboard is made of wood fibers glued together, and used to make furniture, cabinets, moldings, and door skins. While there are many other types of composite wood products (e.g., oriented strandboard, hardboard, etc.), the ATCM applies to HWPW, PB, and MDF.

### B. Composite Wood Product Manufacturing Plants

#### 1. Hardwood Plywood Plants

Plywood is made out of wood veneers and an inner core, where the core may be a wood veneer, lumber, PB, MDF, or a combination of materials (Figure IV-1). The proposed ATCM would apply to HWPW made with either a veneer core or with a composite core composed of PB, MDF, or a combination of PB, MDF, and wood veneers (e.g., combination core). The primary uses of HWPW are for interior wall panels, furniture, flooring, and cabinets. In 2003, HWPW production in the U.S. was estimated to be 1.9-million m<sup>3</sup> (Howard, 2005).

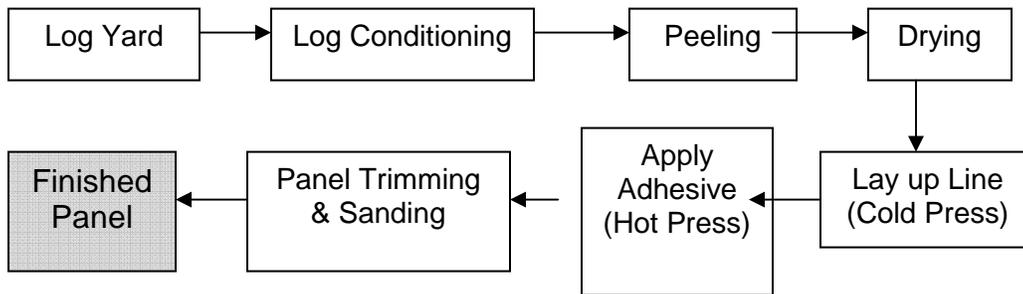
Figure IV-1. Types of Hardwood Plywood



Source: Cognard (2005).

Logs are steamed, then peeled to form a continuous ribbon of thin veneer. The veneer is cut and dried. Processed veneers are stacked onto an assembly line and adhesives applied. Stacked veneers are cold pressed and then hot pressed. After the panels cool, they are trimmed, resized, or sanded.

Figure IV-2. Plywood Manufacturing Process



Source: Cognard (2005).

Plywood panels of  $\frac{3}{8}$ " or thinner typically contain one double glue-line; panels with thicknesses of  $\frac{1}{2}$ ",  $\frac{5}{8}$ ", and  $\frac{3}{4}$ " contain two double glue-lines (Spelter, 1989). A single glue-line application rate is 30-40 lbs per 1,000 ft<sup>2</sup> (Industry Canada, 2005a; 2005b). As such, thicker panels require twice as much glue as thin panels. The glue used may contain HCHO.

## 2. Particleboard Plants

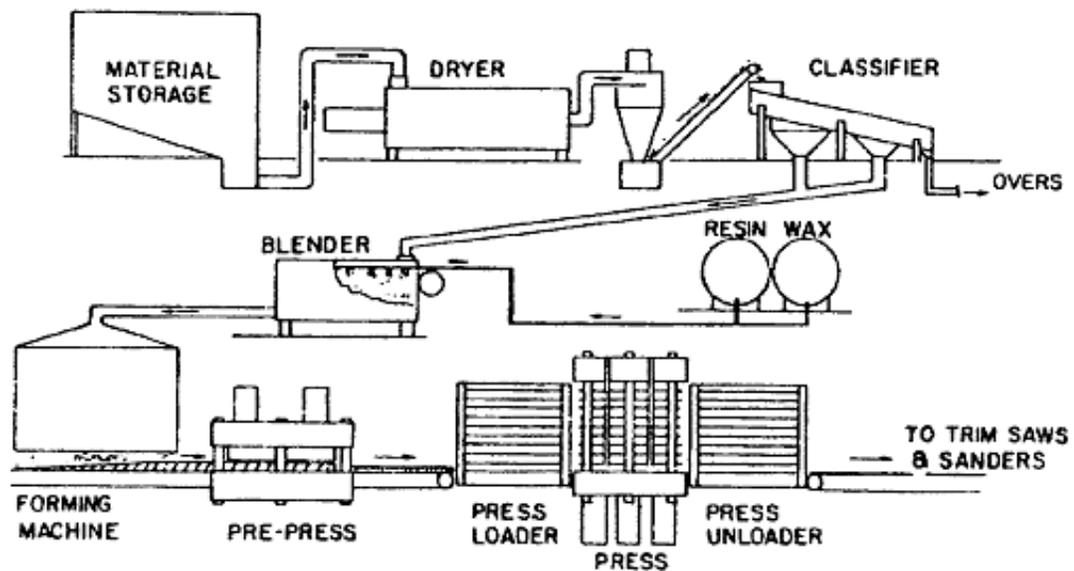
Particleboard (PB) is typically made in three layers: two face layers and a core. The faces of the board consist of finer wood particles than the core. This layered construction promotes more consistent heat transfer during the curing process. In 2003, PB production in the U.S. was 7.1-million m<sup>3</sup> (Composite Panel Association, 2006; Howard, 2005; Industry Canada, 2005a). It is principally used in furniture manufacturing, underlayments, or substrates for countertops.

The five main steps in PB manufacturing are: (1) furnish preparation (i.e., wood particles), (2) resin application, (3) mat formation, (4) hot pressing, and (5) finishing. The furnish is prepared by refining logs and other raw materials into small particles, and drying them to achieve a moisture content of 2 to 7% (Cognard, 2005). Drying the furnish to a specific moisture content is key to ensuring that the proper amount of resin is added prior to manufacturing, which is fundamental to controlling surface HCHO emissions and desired structural properties. As addition of the resin provides moisture to the furnish, it is a critical step insofar as achieving an optimal moisture content at the start of the manufacturing process.

During resin application, resin is mixed with the furnish. In PB, the resin accounts for 5 to 12% of the total weight of the panel depending on the size of the wood particles and the required properties of the panel (e.g., moisture resistance) (Cognard, 2005; Goldboard, 2000). After a UF resin is thoroughly

mixed with the furnish, the mixture is cold-pressed to form a mat, then hot-pressed at cure temperatures ranging from 130 to 150 °C (Cognard, 2005). In comparison, PB made with PF resin requires hot-pressing at temperatures ranging from 180 to 230 °C (Pizzi, 1994). In the finishing process, PB panels are trimmed, cut, and sanded to produce panels of a desired thickness. Figure IV-3 depicts a typical production line for PB manufacturing.

Figure IV-3: Schematic of a Particleboard Manufacturing Line



Source: Wikipedia Contributors, 2006.

### 3. Medium Density Fiberboard (MDF) Plants

In 2003, MDF production was 2.7-million m<sup>3</sup> in the U.S., where it is primarily used in the manufacture of furniture, shelving, molding, and kitchen cabinets (Composite Panel Association, 2006; Howard, 2005). The manufacturing process for MDF is similar to that for PB, except that additional processing is required to prepare the fibers in the furnish (McCallum, 1996; Tetlow, Not Dated). Logs used in the manufacture of MDF are debarked before being chipped with a disk chipper to produce chips of the desired size. After washing, the chips are compacted using a screwfeeder and then fed into a defibrator (or digester) to produce a fine, light-weight pulp. From the defibrator, the pulp enters a blowline, where it mixed with wax and resin before being stored for making panels. This is the main factor contributing to the difference in density between MDF (600 to 800 kg m<sup>-3</sup>) and PB (160 to 450 kg m<sup>-3</sup>).

## C. Resins Currently Used in Composite Wood Products

### 1. General Properties of Resins

The role between resins and wood surfaces is a very complex interaction and entails many different theories regarding bond formation and thermodynamic processes. First, we must define some terms in order to describe some of the interactions that occur (USDA, 1999):

- Adhesive is a substance capable of holding materials together by surface attachment.
- Adherend is a substrate held to another substrate by an adhesive.
- Adhesion is defined as “the state in which two surfaces are held together by interfacial forces, such as valence forces, interlocking action, or both.”
  - Valence forces are the interactions of atoms, ions, and molecules by the adhesive and the adherend.
  - Interlocking action means surfaces are held together by an adhesive that has penetrated the porous wood surface.

The primary mechanism by which adhesives fasten to porous wood surfaces is mechanical interlocking (Frihart, 2004), which takes place below the surface of the wood. The adhesive penetrates beyond the damaged fibers of the wood surface into the next two to six wood cell layers. The deeper the adhesive can penetrate into the wood, the more effective the mechanical interlocking. Also, if the adhesive is able to diffuse into the cell walls of the wood while curing takes place, the strength of the bond can exceed the strength of the wood itself.

Three intermolecular attraction forces are important to the bond formation between adhesive and the molecular structure of wood (Vick, 1999). They are:

1. Dipole-dipole forces – positively and negatively charged polar molecules that have powerful attractions toward other polar molecules;
2. London forces – a weaker attraction of polar and non-polar molecules. These forces are weaker than dipole-dipole forces but increase as the number of atoms or molecules increase; and
3. Hydrogen bonds – a strong attraction between a positively charged atom from a polar molecule and the electronegative atom of another molecule. Hydrogen bonds are usually stronger than dipole-dipole forces. Hydrogen bonds are probably the most important intermolecular force due to the number of hydroxyl groups on cellulosic surfaces.

Adhesion is nearly completed after the transformation of the adhesive from liquid to solid form. There are two mechanisms in which an adhesive changes from liquid to a solid form (Connor, 2001). This transformation may be a physical change (thermoplastics) or a chemical change (thermosettings). In thermoplastics, the solid form may occur by a loss of solvent from the adhesive

through evaporation or diffusion into the wood, or cooling of molten adhesive on a cooler surface. For thermosets, the mechanism is through a chemical polymerization to form crosslinked structures.

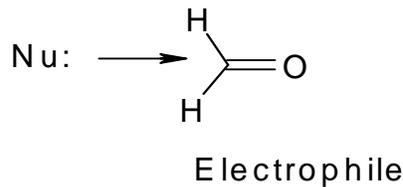
## 2. Formaldehyde-containing Resins

The most prevalent types of resin used in composite wood products contain HCHO (Frihart, 2005). Compounds such as urea, phenol, and melamine are combined with HCHO to develop different formulations of resins for PB, MDF, plywood, and other composite wood products. The chemical reaction involves a nucleophile (electron-rich compound), such as urea, phenol, and melamine, with an electrophile (electron-poor compound), such as HCHO. There are three reaction steps involved with HCHO adhesives (Frihart, 2005):

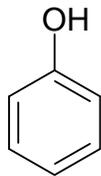
1. Formaldehyde reacting with a nucleophile to form a hydroxymethyl derivative (Figure IV-4);
2. Condensation of two hydroxymethyl groups to form a bismethylene ether group, with loss of a water molecule; and
3. Elimination of HCHO from the bismethylene ether to form a methylene bridge.

The rate of reaction depends on the pH of the environment, the nucleophile, temperature, and the addition of catalysts or retarders.

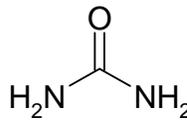
Figure IV-4. Reaction between a Nucleophile (Nu) and Formaldehyde



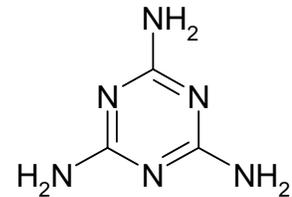
Nucleophiles



Phenol



Urea



Melamine

The majority of formaldehyde-containing resins are waterborne. The amount of water in the resin is very critical for the polymerization of the resin. Too much water hinders the reaction; too little water reduces the mobility of the resin and limits the polymerization process. For resin formulation, the mole ratio of HCHO needs to be greater than that of the co-reactant (Frihart, 2005), which is needed

to bring about the required reactions to form a crosslink-type solid. All formulations are also adjusted to decrease the amount of HCHO emissions and to insure good curing times and fast set rates.

a. Urea-Formaldehyde Resins

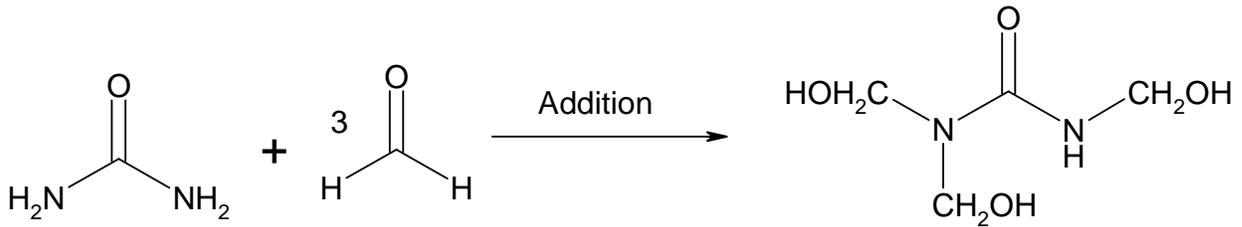
Urea-formaldehyde (UF) resins have been around since the early 1920's and have been the most dominant adhesive for PB, MDF, and HWPW (Meyer and Hermanns, 1986). In the U.S. alone, it is estimated that the demand for UF resins will reach over 2.4 billion pounds in 2007. Approximately 89% of the UF produced in North America is used for wood adhesives (Kennedy, 2005). Urea-formaldehyde resins are used for interior applications and need a dry environment. They cure fast and are relatively inexpensive. There are many advantages and disadvantages concerning the use of UF resins (Table IV-1).

Table IV-1. Advantages and Disadvantages of Urea-formaldehyde Resins <sup>1</sup>	
Advantages	Disadvantages
<ul style="list-style-type: none"> <li>• Low cost</li> <li>• Rapid cure rate</li> <li>• Light color</li> <li>• Non-flammable</li> <li>• Resistant to microorganisms</li> </ul>	<ul style="list-style-type: none"> <li>• Not water-resistant</li> <li>• Continuation of HCHO emissions</li> <li>• Combination of moisture and heat depolymerizes resin</li> </ul>
<p><sup>(1)</sup> <u>Source:</u> Frihart (2005).</p>	

i. Manufacturing Urea-formaldehyde (UF) Resins

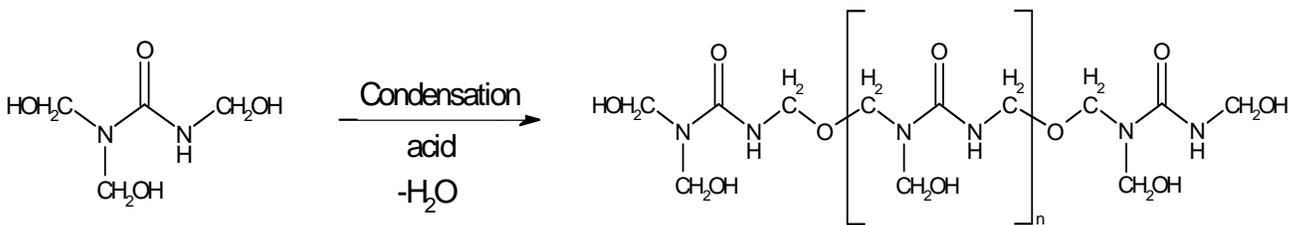
Urea and HCHO are the building blocks for UF resins. Urea is synthesized by combining ammonia (NH<sub>3</sub>) and carbon dioxide (CO<sub>2</sub>) under heat and pressure. Formaldehyde, with the addition of a catalyst, is manufactured from methanol (CH<sub>3</sub>OH) (Orica, 1999). There are two main steps involved in the manufacturing of UF resins (Connor, 1996). The first stage involves the addition of HCHO with urea. Under basic conditions (pH 8 to 9), urea is hydroxymethylated to form mono-, di-, and trihydroxymethylureas (Figure IV-5).

Figure IV-5. Addition of Urea and Formaldehyde to Form Hydroxymethylureas



The second stage involves a condensation reaction under acidic conditions (about pH 5) to generate oligomers that will polymerize until a target viscosity is obtained (Figure IV-6). Polymerization is slowed by raising the pH and cooling the reaction. Water is then removed by vacuum distillation to achieve a desired solids content (i.e., 60 to 65%). Urea is often added to the resin to reduce HCHO emissions and obtain the desired formaldehyde-to-urea mole ratio.

Figure IV-6. Condensation Reaction and Polymerization of UF Resins



The reactions that occur during UF resin synthesis are reversible. During the forward reaction, water is eliminated. However, if moisture interacts with the UF resin, depolymerization may occur, leading to hydrolysis or the release of HCHO.

## ii. Curing Urea-formaldehyde (UF) Resins

During the hot pressing of a composite wood product, polymerization and condensation of the resin is completed and the release of free HCHO occurs. Hot-press temperatures for UF resins usually range between 100 to 120 °C. This is a critical step in the manufacturing process since too much heat can hydrolyze the UF resin into urea and HCHO, which degrades the bond and releases even more HCHO (Conner, 2001). Table IV-2 displays some of the characteristics of UF resins:

Table IV-2. Characteristics of Urea-formaldehyde (UF) Resins <sup>1</sup>	
Category	Summary
Form	Available as a dry powder or liquid(s)
Properties	High in dry strength; moderately durable under damp conditions; low resistance to temperatures > 49 °C; white or tan in color
Preparation	Liquid use as received; powder form mix with water; hardeners, extenders, and fillers may be added; hot press at 100 to 120 °C.
Uses	HWPW for interior use and furniture; interior PB and MDF for cabinets, underlayment, flush doors, and furniture core stock
<sup>(1)</sup> Source: Eckelman (1997).	

b. Phenol-formaldehyde (PF) Resin

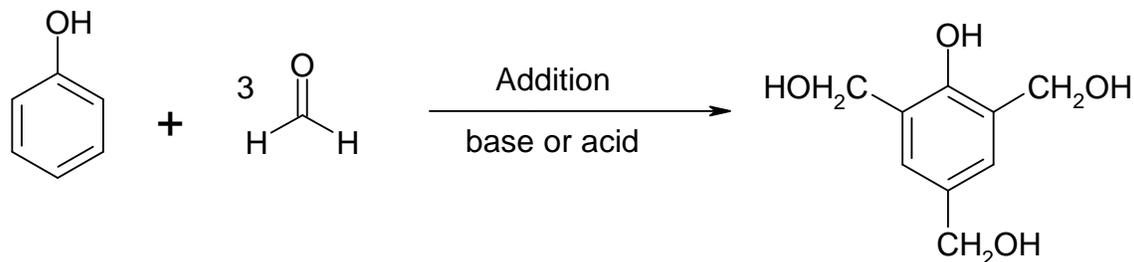
Phenol-formaldehyde (PF) resins were first introduced and commercially developed in the early 20<sup>th</sup> century by Leo Baekeland (Society of the Plastics Industry, 1997). They are one of the oldest classes of synthetic polymers used in composite wood products. Phenol-formaldehyde resins are used mainly for exterior applications because of their high water resistance and higher strength retention after water soaking. They also have outstanding durability and high polymer strength due to good adhesion to wood surfaces. Approximately 32% of the total 1.78 metric tons of resin solids is consumed in North America (Zheng, 2002). The primary composite wood products that use PF resins are oriented strandboard and softwood plywood, which are mainly used for exterior sidings. They may be unsuitable for decorative applications, such as paneling and furniture, because of the inherent dark color of the resin. Although PF resins have many advantages, some of their disadvantages are longer press times and higher press temperatures, which results in higher energy consumption and lower productivity. However, by altering reaction temperature, reaction time, catalyst type, and formaldehyde-to-phenol ratio, some disadvantages may be overcome (Frihart, 2005).

There are two main types of phenolic resins: resole and novolac. Novolac resins are produced using an acid catalyst and excess phenol; whereas, resole resins are produced with a base catalyst and excess formaldehyde (Durez, Not Dated). Most wood adhesive applications use resole resins because they provide a soluble adhesive that has good wetting properties and the cure is delayed until activated by heat, allowing additional time for product assembly.

### i. Phenol-formaldehyde (PF) Resin Chemistry

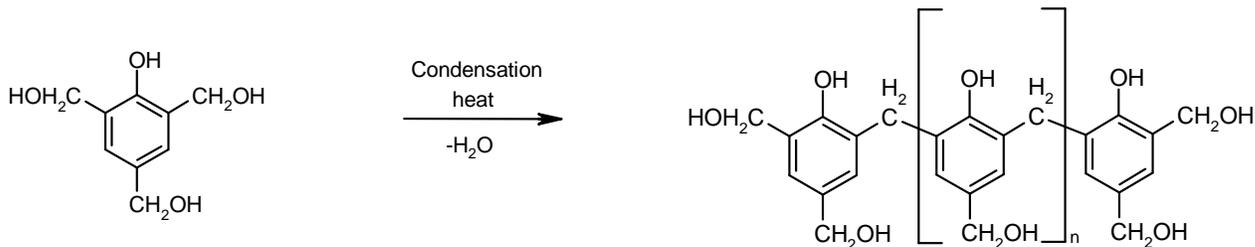
Phenolic resins are developed through a polycondensation reaction of phenol and HCHO (Frihart, 2005). Phenols may react with HCHO in both the ortho- and para- positions of the hydroxyl group in either a basic or acidic environment (Figure IV-7).

Figure IV-7. Addition Reaction for Phenol and Formaldehyde



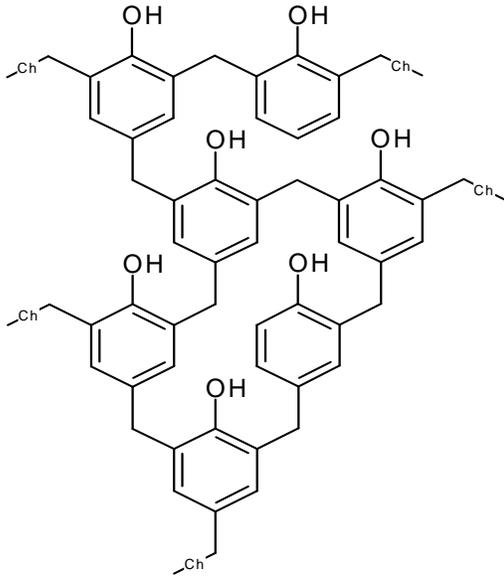
The second stage of resin development involves the formation of linear phenol-formaldehyde oligomers through heat and condensation. The oligomers are created by reaction of the methylol groups with other phenol or methylol phenol compounds (Figure IV-8).

Figure IV-8. Phenol-formaldehyde (PF) Resin: Condensation Reaction



After the formation of the linear oligomers, polymerization occurs to create a phenol-formaldehyde crosslinked polymer network (Figure IV-9).

Figure IV-9. Phenol-Formaldehyde Cross-linked Polymer



Phenol Formaldehyde Crosslinked Polymer

Unlike UF resins, PF reactions are not reversible and are pressed at a higher temperature (190 °C or higher) (Eckelman, 1997). Table IV-3 lists some of the characteristics involved with PF resins.

Table IV-3. Characteristics of Phenol-formaldehyde (PF) Resins <sup>1</sup>	
Category	Summary
Form	Available as a dry powder or liquid(s)
Properties	High in dry and wet strength; very resistant to moist conditions and high temperatures; dark red color
Preparation	Liquid form use as received; powder form mixed with alcohol or water; extenders and fillers usually added to liquid form; press temperatures are higher (up to 200 °C)
Uses	Exterior use in softwood plywood, OSB, hardboard
<sup>(1)</sup> <u>Source</u> : Eckelman (1997).	

c. Melamine-containing Formaldehyde (MF) Resins

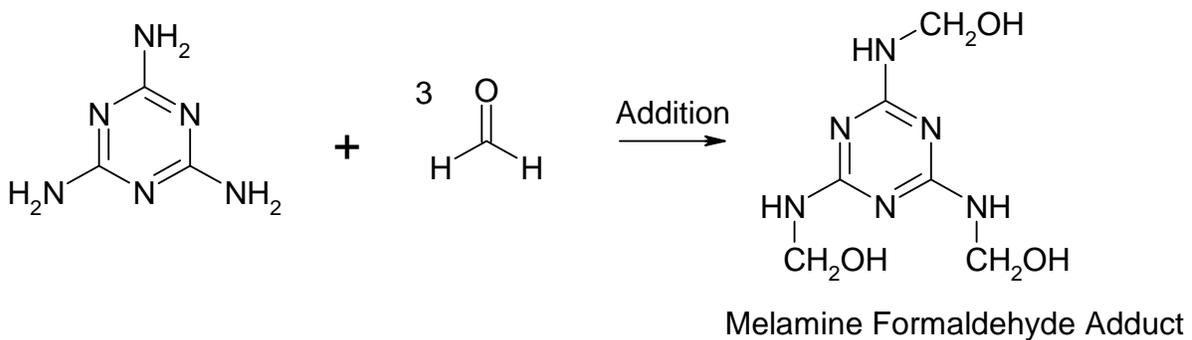
Like PF resins, melamine-formaldehyde (MF) and melamine-urea-formaldehyde (MUF) resins are resistant to moist conditions (Marra, 1992). They are most commonly used for exterior and semi-exterior plywood and PB. In addition, MF

is used for decorative laminates, paper treating, and paper coating. One drawback of MF resins is the cost of melamine (e.g., \$63 to \$68 per pound) (ICIS Pricing, 2006). This contributed to the development of MUF resins, which still have water resistance, but at a lower cost. The MUF resins can be viewed as a less expensive MF resin that has lower durability, or as a more expensive UF resin that has better water resistance. The MF and MUF resins are also lighter in color compared to PF resins.

i. Melamine Chemistry

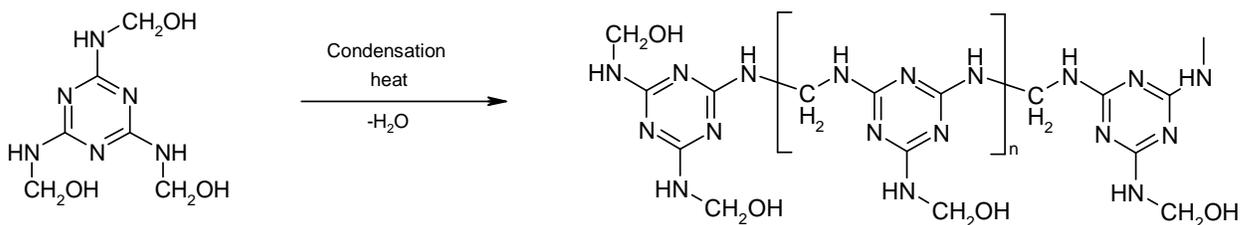
The formation of melamine-based resins is very similar to that of an UF resin (Frihart, 2005). However, the addition of HCHO to the amino groups of melamine is faster and more complete than to urea because melamine is a stronger nucleophile than urea (Figure IV-10).

Figure IV-10. Addition Reaction for Formaldehyde and Melamine



Melamine can potentially react with six HCHO molecules to form two methylol groups on each exocyclic amine group. This condensation reaction can occur under acidic, neutral, and slightly basic conditions (Figure IV-11).

Figure IV-11. Condensation Reaction of Hydroxymethylated Melamines



Furthermore, the release of HCHO during the condensation reaction is less prominent than for UF resins. During polymerization, pH is lowered and temperature is raised to insure a complete reaction. In addition, melamine

significantly reduces HCHO emissions (Dijkman, 2004). Table IV-4 lists some of the properties and uses for melamine-based resins.

Table IV-4. Summary of Melamine-based Resin Properties and Uses <sup>1</sup>	
Category	Summary
Form	Powder with blended catalyst; may use up to 40% melamine with urea; white to tan; colorless bondline
Properties	High dry and wet strength; very resistant to water and damp conditions
Preparation	Powder mixed with water and applied at room temperature; cured in hot press (120°C - 150°C)
Uses	Typically a fortifier in UF resins; used in HWPW and MDF
<sup>(1)</sup> <u>Source</u> : Eckelman (1997).	

### 3. No added Formaldehyde Resins

For the past 70-years, HCHO has been an essential solvent in composite wood product resins. In fact, greater than 95% of wood adhesives are formaldehyde-based (Dunky, 2005). However, there are “no added” HCHO resins that are currently in the composite wood products market that are developing into a feasible option for manufacturers. Examples of “no added” HCHO resins are polydiphenylmethane diisocyanate (pMDI), soy-based, polyvinyl acetate (PVA), and tannin resins.

#### a. Polydiphenylmethane Diisocyanate (pMDI) Resins

Isocyanate-based adhesives have been commercially available since the 1940’s, but their use increased substantially in the 1970’s (Eckelman, 1997). Polydiphenylmethane diisocyanate (pMDI) is primarily used in oriented strandboard production and applications for strawboard products, but has been commercially available for other wood composites, such as MDF and PB (Ecology Action, 2004). The cost of pMDI is considerable; however, these resins have a high reactivity and efficiency in bonding to wood surfaces or adhering to difficult surfaces (Frihart, 2005). The chemical bonds in pMDI are stronger and more stable than the condensation reactions of UF or PF (Pizzi, 1994). There is even more demand for pMDI-bonded products where increased water resistance is required since pMDI resins are resistant to hydrolysis. Table IV-5 lists the advantages and disadvantages of pMDI.

Table IV-5. Advantages and Disadvantages of Polydiphenylmethane Diisocyanate (pMDI) Resins<sup>1</sup>

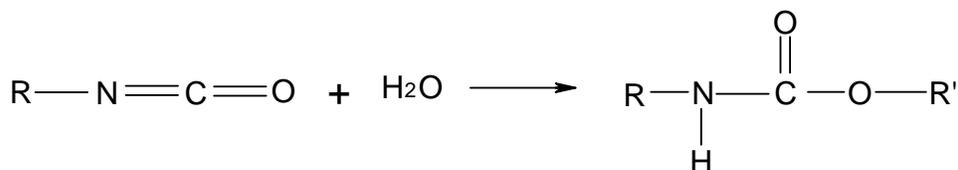
Advantages	Disadvantages
<ul style="list-style-type: none"> <li>• Tolerance for higher moisture content in wood</li> <li>• Less MDI is needed on a weight basis to form bonded material</li> <li>• Faster press cycles</li> <li>• Lower press temperatures</li> <li>• No formaldehyde emissions</li> </ul>	<ul style="list-style-type: none"> <li>• Higher cost</li> <li>• Use of mold releases for metal press platens</li> <li>• Health risks to workers (isocyanates)</li> <li>• Must be stored away from moisture to prevent precure</li> </ul>

<sup>(1)</sup> Source: Marra (1992).

#### i. Polydiphenylmethane Diisocyanate (pMDI) Chemistry

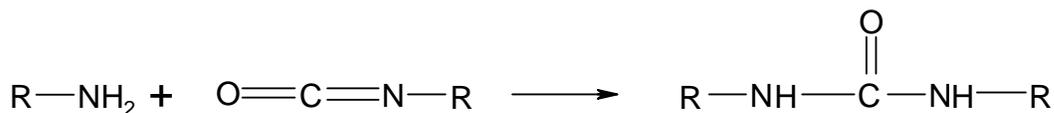
The first reaction for the polymerization of MDI that occurs is the combination of the isocyanate and water to form a urethane bridge (Figure IV-12). Once isocyanate reacts with water, the rest of the process proceeds rapidly if there is enough isocyanate for the reaction. The result is an unstable carbamic acid product that decomposes to form an amine and carbon dioxide (Pizzi, 1994).

Figure IV-12. Isocyanate and Water React to Produce a Urethane



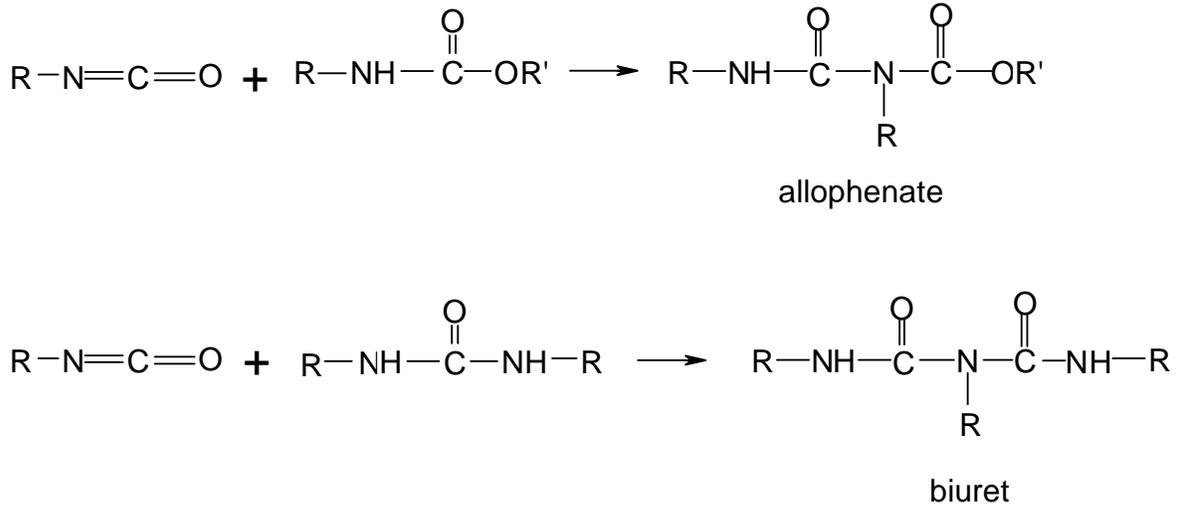
The amine formed by this reaction will react immediately with additional isocyanates to form a substituted urea compound (Figure IV-13).

Figure IV-13. Reaction of an Amine and Isocyanate to Form a Substituted Urea



Cross-linking and hardening occur when amine groups from the urethane react with the substituted urea to form allophenate and biuret bridges (Figure IV-14).

Figure IV-14. Urethane Bridge and Substituted Ureas React with Isocyanates to Produce Allophenate and Biuret Bridges



This rapid polymerization and ability to form bonds in the presence of higher moisture content gives MDI advantages in several applications. When used in core areas that might have higher moisture contents, MDI bonds to wet lumber. Another use of MDI is the manufacturing of strawboard. Because of the low polarity of MDI, it is able to penetrate through the waxy coating of straw and cure readily (Frihart, 2005). Table IV-6 lists some of the MDI resin characteristics.

Table IV-6. Characteristics of MDI Resins <sup>1</sup>	
Category	Summary
Form	Liquid resin or water emulsions; can create wide variety of adhesives; light brown liquid and clear bondline
Properties	Excellent adhesion to wood and other materials, such as metals and plastics; resistant to high moisture and temperatures; excellent chemical aging resistance
Preparation	One-part adhesive cures by heat or moisture; two-parts resins cure upon mixing; very rapid cure
Uses	Used mainly in OSB, PB, MDF or flakeboards
<sup>(1)</sup> Source: Eckelman (1997).	

## b. Soy-based Resins

Soy-based resins have been used in the manufacture of plywood for more than 70-years (United Soybean Board, 2004). However, early soy resins had low solids, slow press times, and, most importantly, poor water resistance (Wescott et al., 2006). This limited the use of soy resins to only interior applications. Since the introduction of petroleum derived resins (e.g., UF or PF), soy-based resins rapidly diminished from the market because they were inferior in performance and more expensive. In the last 40-years, UF and PF have been the most popular resins used in composite wood products. In recent years, environmental concerns from volatile organic compounds, such as free-formaldehyde from UF resins and the constant increase of petroleum prices, have revitalized interests in developing soy-based resins (Lorenz et al., 1999).

The primary ingredient in soy-based resins is soy flour, which is produced by grinding the meal that remains after removing soybean oil (Wescott and Frihart, 2004). Soy flour is high in protein and contains many side-chain reactive amino acid groups and is believed to have the ability to react with other cross-linking agents to create a water-resistant resin.

### i. Soy-based Resin Preparation

In a study by Wescott and Frihart (2004), soy resins were prepared in a low-temperature environment. They are formulated with water, sodium hydroxide (8% to 12%), and a solubilizing agent (e.g., a glycol), along with soy flour. The ingredients were combined and heated to 70 °C. Water durability was modified by the addition of a copolymer or synthetic resin to engage the polymerization process.

New soy resins are beginning to show promise in both performance and economics compared to the UF and PF resins. Soy resins are also safer to handle and reduce the amount of free HCHO that can be emitted from composite wood products. Chapter V describes a range of different soy-based resins that are being explored today for composite wood products.

## c. Polyvinyl Acetates (PVA)

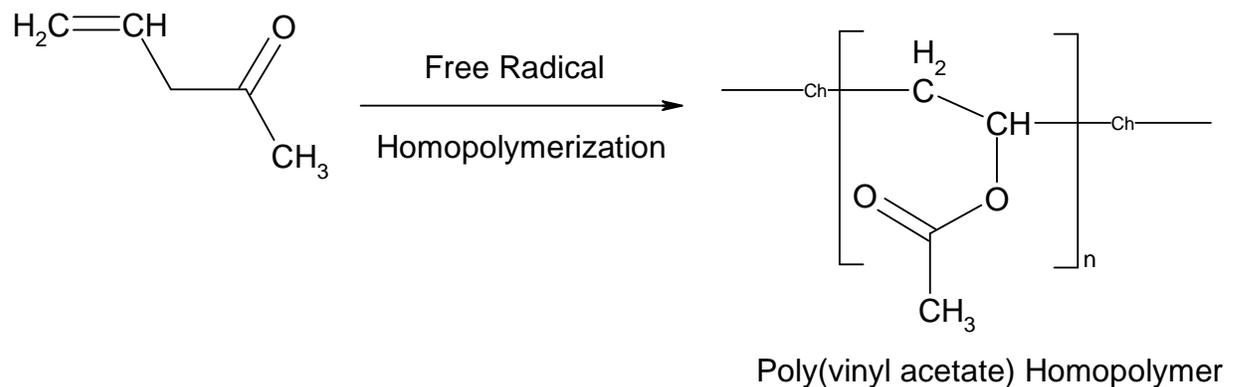
Polyvinyl acetate (PVA) is known throughout as your common “white glue” used mainly for HWPW veneers and wood bonding in furniture. This resin sets quickly at room temperature and has a high dry strength, but is less resistant to moisture, humidity, or high temperatures (Eckelman, 1997). Because PVA loses bonding capacity at temperatures over 70 °C, it is used mainly for interior applications. However, cross-linking agents, such as chromium complexes, may be added to the resin to withstand higher moisture contents and temperatures (Connor, 2001).

Polyvinyl acetate is a linear polymer that is flexible in nature and exhibits good flow on the surface of wood (Frihart, 2005). Since PVA has a high content of acetal groups, the resin is able to form hydrogen bonds with wood for a good interfacial adhesion. The polymer flexibility of PVA provides a conformable bond if the wood expands or contracts (Marra, 1992).

i. Polyvinyl Acetate (PVA) Chemistry

Polyvinyl acetate is a self-polymerizing resin that is initiated under free radical conditions of the monomer vinyl acetate. By adding ethylene, the polymer chains can be modified to form a PVA copolymer which creates a more flexible resin (Figure IV-15).

Figure IV-15. Polymerization of PVA



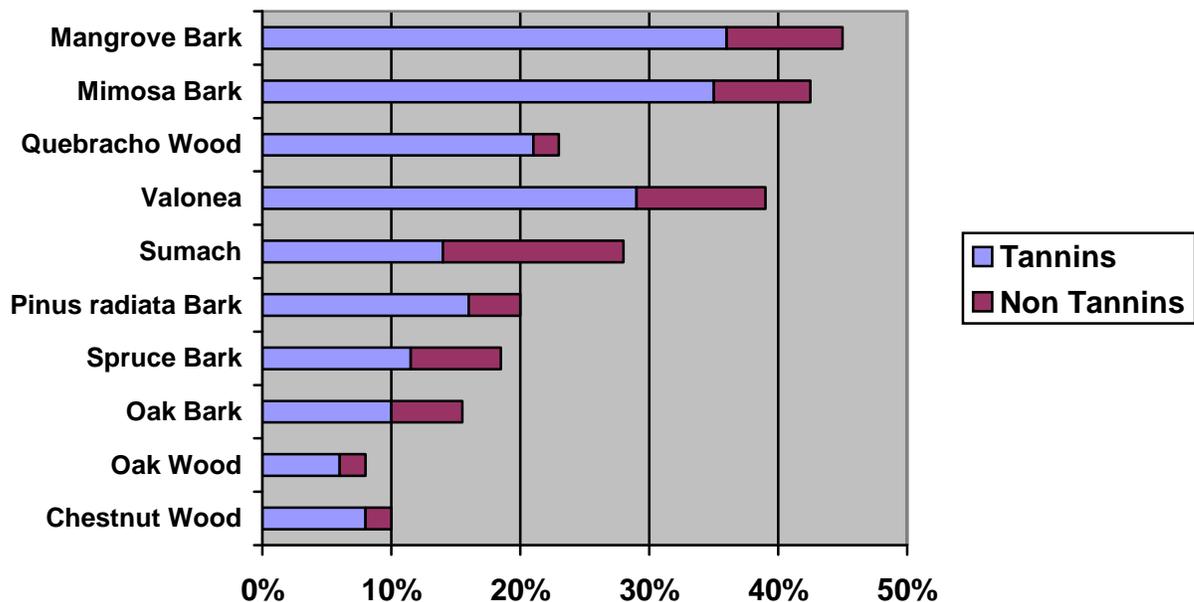
Cross-linking PVA with other resin additives such as glyoxal, HCHO resins, or isocyanates, can convert the PVA from a thermoplastic to a thermoset (see subsection IV.C.1). This improves resistance to high moisture and higher temperatures (Frihart, 2005). Table IV-7 lists some characteristics of PVA.

Table IV-7. Characteristics of Polyvinyl Acetate (PVA) Resins <sup>1</sup>	
Category	Summary
Form	Several brands available; vary in properties; sold in liquid forms
Properties	High dry strength; low resistance to moisture and elevated temperatures; white or yellow in color
Preparation	Ready to use liquid; applied at room temperature
Uses	HWPW; furniture assembly
<sup>(1)</sup> Source: Eckelman (1997).	

d. Tannin-based Resins

Attempts have been made to depart from the use of petroleum derived products, such as phenol, to using natural resources instead of synthetic resins. Tannins, as a natural substitute for phenols, are a natural phenolic-type material that is extracted from the bark or heartwood of many plant species (Roffael et al., 2000) (Figure IV-16). Mangrove and mimosa bark contain comparably high levels of extractives, while the amount from spruce bark is relatively low. Commercially available tannin extracts that are used in manufacturing include: *Acacia* sp. (wattle or mimosa), *Schinopsis* sp. (quebracho), *Tsuga* sp. (hemlock), *Rhus* sp. (sumac), and *Pinus* sp. (Pizzi, 2006).

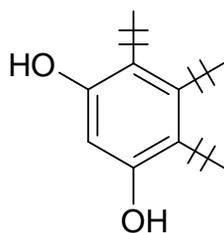
Figure IV-16. Average Yield of Extractives from Different Woods and Barks <sup>1</sup>



<sup>(1)</sup> Source: Roffael et al., 2000.

Tannins are categorized as either hydrolyzable or condensed. Hydrolyzable tannins are used more for medicinal purposes and not in adhesive research. Condensed tannins, which are used in the preparation of resin adhesives, constitute more than 90% of the total world production (Sellers and Miller, 2004). Tannins are more reactive than phenol resulting in water-resistant bonds when polymerized with HCHO (Santana et al., 1997). This reactivity is due to their “A-ring,” which is resorcinolic in nature (Figure IV-17). The A-ring ensures the rate of reaction to be 10 to 50 times faster than phenol (Kim et al., 2003).

Figure IV-17. The A-Ring Unit of a Tannin Compound



Tannins have their limitations compared to synthetic resins. They have a high viscosity, restrictions on availability, and are highly reactive (Frihart, 2005). This causes a short pot-life for tannin resins. However, other hardeners may be added to prolong tannin pot-life (Trosa and Pizzi, 2001). Reactions involving tannin compounds are very complex, but studies have shown that HCHO reacts with the free C6 and C8 sites on the A-ring to form the adhesive (Kim et al., 2003). This characteristic results in HCHO emissions comparable to the wood itself. Research in tannin adhesives has continued to discover more low-formaldehyde resins.

#### D. References

Cognard P. 2005. Woodworking and furniture adhesives. Part 5: Applications and end uses. Accessed: 20 September 2006. From: <http://www.specialchem4adhesives.com/resources/articles/printarticle.aspx?id=1235>

Composite Panel Association (CPA). 2006. 2005 North American Shipments Report: Particleboard, Medium Density Fiberboard, Hardboard. CPA, Gaithersburg, MD. 18 pp.

Connor AH. 1996. Urea-formaldehyde adhesive resins. In: Salamone JC (ed). Polymeric Materials Encyclopedia, Volume 11, T-Z, p. 8496-8501. CRC Press, Inc., Boca Raton. ISBN: 0-8493-2470-X.

Connor AH. 2001. Wood: Adhesives. In: Buschow KHJ (ed). Encyclopedia of Materials: Science and Technology, p. 9583-9599. Elsevier Science Ltd., Amsterdam. ISBN: 0-08-0431526.

Dijkman H. 2004. DSM Melamine: Growing a profitable business. From: [http://www.dsm.com/en\\_US/downloads/invest/dijkman\\_24\\_sept.pdf](http://www.dsm.com/en_US/downloads/invest/dijkman_24_sept.pdf) Accessed: 4 February 2007.

Dunky M. 2005. Resins for ultra low formaldehyde emission according to the Japanese F\*\*\*\* quality. From: <http://www.forestprod.org/adhesives05dunky3.pdf> Accessed: 4 February 2007.

Durez Corporation. Not Dated. Phenolic molding composites. From: <http://www.durez.com/product.pdfs/phen.mold.comp/pmc.tech.overview.pdf> Accessed: 4 February 2007.

Eckelman CA. 1997. Brief survey of wood adhesives. FNR 154, Forestry & Natural Resources, Purdue University, Cooperative Extension Service, West Lafayette, IN. 10 pp.

Ecology Action. 2004. Wood panels: Plywood, OSB, MDF, and Ag Waste Boards. Accessed: 2 February 2007. From: [http://www.ecoact.org/Programs/Green\\_Building/green\\_Materials/wood\\_panels.htm](http://www.ecoact.org/Programs/Green_Building/green_Materials/wood_panels.htm)

Frihart CR. 2004. Adhesive interactions with wood. In: Forest Products Laboratory. Fundamentals of Composite Processing: Proceedings of a Workshop. General Technical Report FPL-GTR-149, p. 29-38. USDA, Forest Service, Forest Products Laboratory, Madison, WI.

Frihart CR. 2005. Wood adhesion and adhesives. In: Rowell RM (ed). Handbook of Wood Chemistry and Wood Composites. Chapter 9, p. 215-278. CRC Press, Inc., Boca Raton.

Goldboard Development Corporation. 2000. Gluing: Urea-formaldehyde (UF) resin. From: [http://www.goldboard.com/products/gluing\\_uf.html](http://www.goldboard.com/products/gluing_uf.html) Accessed: 12 December 2001.

Howard JL. 2005. U.S. Forest Products Annual Market Review and Prospects, 2001-2005. Research Note FPL-RN-0299, USDA, Forest Service, Forest Products Laboratory, Madison, WI. 11 pp.

ICIS Pricing. 2006. Melamine (USA): 9<sup>th</sup> August 2006. Accessed: 2 February 2007. From: [http://www.icispricing.com/il\\_shared/Samples/SubPage10100043.asp](http://www.icispricing.com/il_shared/Samples/SubPage10100043.asp)

Industry Canada. 2005a. Wood-based panel products: Technology roadmap. I. Introduction and overview. From: <http://strategis.ic.gc.ca/epic/internet/infif.nsf/en/oc01504e.html> Accessed: 13 April 2006.

Industry Canada. 2005b. Wood-based panel products: Technology roadmap. II. Panels in perspective. From: <http://strategis.ic.gc.ca/epic/internet/infif.nsf/en/oc01505e.html> Accessed: 13 April 2006.

Kennedy HJ. 2005. The North American Wood Adhesives Market. Accessed: 4 February 2007. From: <http://www.forestprod.org/adhesives05kennedy.pdf>

Kim S, Y-K Lee, H-J Kim, and HH Lee. 2003. Physico-mechanical properties of particleboards bonded with pine and wattle tannin-based adhesives. *Journal of Adhesion Science & Technology*, 17(14): 1863-1875.

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

Marra AA. 1992. *Technology of Wood Bonding: Principles in Practice*. Chapter 4, p. 61-101. Van Nostrand Reinhold Company, New York. 454 pp. ISBN: 0442007973.

McCallum D. 1996. The manufacturing process: Medium density fibreboard. From: <http://sres-associated.anu.edu.au/fpt/mdf/manufacture.html> Accessed: 23 February 2007.

Meyer B and K Hermanns. 1986. Formaldehyde release from wood products: An overview. In: Meyer B, BA Kottes Andrews, and RM Reinhardt (eds). *Formaldehyde Release from Wood Products*. ACS Symposium Series, 316: 1-16.

Orica Limited. 1999. Urea formaldehyde resin. Accessed: 4 February 2007. From: [http://www.pacia.org.au/uploaditems/docs/3.urea\\_formaldehyde\\_resin.pdf](http://www.pacia.org.au/uploaditems/docs/3.urea_formaldehyde_resin.pdf)

Pizzi A. 1994. *Advanced Wood Adhesives Technology*. Chapter 8, p. 273-282. Marcel Dekker, Inc., New York.

Pizzi A. 2006. Recent developments in eco-efficient bio-based adhesives for wood bonding: Opportunities and issues. *Journal of Adhesion Science & Technology*, 20(8): 829-846.

Roffael E, B Dix, and J Okum. 2000. Use of spruce tannin as a binder in particleboards and medium density fiberboards (MDF). *Holz als Roh- und Werkstoff*, 58: 301-305.

Santana MAE, MGD Baumann, and AH Connor. 1997. Utilization of black wattle bark and tannin liquefied in phenol in the preparation of resol-type adhesives. From: <http://www.fpl.fs.fed.us/documnts/pdf1997/santa97a.pdf> Accessed: 4 February 2007.

Sellers T Jr and GD Miller Jr. 2004. Laboratory manufacture of high moisture southern pine strandboard bonded with three tannin adhesive types. *Forest Products Journal*, 54(12): 296-301.

(The) Society of the Plastics Industry, Inc. 1997. The phenolic advantage. From: <http://www.phenolics.org/products/PhenolicNL.htm> Accessed: 11 April 2001.

Spelter H. 1989. Plywood Manufacturing Cost Trends, Excluding Wood, in Western U.S. Mills: 1975-1988. General Technical Report FPL-GTR-64. USDA, Forest Service, Forest Products Laboratory, Madison, WI. 12 pp.

Tetlow K. Not Dated. Composite Panels: Particleboard and Medium-density fiberboard. Accessed: 28 February 2007. From: <http://archrecord.construction.com/resources/conteduc/archives/0512weyerhaeuser-1.asp>

Trosa A and A Pizzi. 2001. A no-aldehyde emission hardener for tannin-based wood adhesives for exterior panels. Holz als Roh- und Werkstoff, 59: 266-271.

United Soybean Board. 2004. Soy-based composites technical research. From: <http://www.omnitechintl.com/pdf/Composites%20-%20T.pdf> Accessed: 4 February 2007.

U.S. Department of Agriculture (USDA). 1999. Glossary. In: Forest Products Laboratory. Wood Handbook – Wood as an Engineering Material. General Technical Report FPL-GTR-113. USDA, Forest Service, Forest Products Laboratory, Madison, WI.

Vick CB. 1999. Adhesive bonding of wood materials. In: Forest Products Laboratory. Wood Handbook – Wood as an Engineering Material. General Technical Report FPL-GTR-113, Chapter 9. USDA, Forest Service, Forest Products Laboratory, Madison, WI.

Westcott JM and CR Frihart. 2004. Competitive soybean flour/phenol-formaldehyde adhesives for oriented strandboard. In: Tichy RJ and V Yadama (eds). 38<sup>th</sup> International Wood Composites Symposium Proceedings, p. 199-206. Washington State University, Pullman, WA.

Westcott JM, CR Frihart, and AE Traska. 2006. High-soy-containing water-durable adhesives. Journal of Adhesion Science & Technology, 20(8): 859-873.

Wikipedia contributors. 2006. Particle board. Accessed: 5 September 2006. From: [http://en.wikipedia.org/wiki/particle\\_board](http://en.wikipedia.org/wiki/particle_board)

Zheng J. 2002. Studies of PF Resole/Isocyanate Hybrid Adhesives. Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA. 213 pp. Accessed: 4 February 2007. From: [http://scholar.lib.vt.edu/theses/available/etd-01072003-200607/unrestricted/Jun\\_Zheng\\_Dissertation.pdf](http://scholar.lib.vt.edu/theses/available/etd-01072003-200607/unrestricted/Jun_Zheng_Dissertation.pdf)

## V. Assessment of Best Available Control Technology

In this chapter, the technical basis for the proposed Phase 1 and Phase 2 standards for HWPW, PB, and MDF are presented in consideration of BACT. For this ATCM, BACT is defined as HWPW, PB, and MDF meeting the proposed Phase 2 emission limits in Tables V-21, V-23, and V-25, respectively, through a combination of process- and resin-related modifications. The candidate resin systems for meeting BACT are listed below:

- HWPW -- Phase 2 Standard (0.05 ppm)
  - UF (mole ratio  $\approx$  1.2 to 1.4) + 15% Melamine
  - PVA
  - PVA-Soy
- PB -- Phase 2 Standard (0.09 ppm)
  - UF (mole ratio  $\approx$  0.8 to 1.1) + 8% Melamine
  - UF (mole ratio  $\approx$  0.8 to 1.1) + Scavengers
  - PF
- MDF – Phase 2 Standard (0.11 ppm)
  - UF (mole ratio  $\approx$  0.9 to 1.2) + 12% Melamine
  - UF (mole ratio  $\approx$  0.9 to 1.2) + Scavengers
  - pMDI

The above resin systems reflect staff's assessment of BACT, which recognizes that manufacturers that choose to use UF resins have one or more options for reducing their HCHO emissions to meet the proposed Phase 2 standards. In section C, we summarize the results of studies on resins used to make HWPW, PB, and MDF. In section D, we summarize the results of studies on candidate low-formaldehyde resin systems. In section E, the technical basis for the proposed Phase 2 limits is described. In general, staff projects that BACT will be based on reformulated UF resins. However, the proposed regulation provides an incentive for panel manufacturers to convert to no added HCHO resins early by not having to comply with the requirement to perform quarterly emission tests of their products under a third party certification program.

### A. Introduction

The range of resin systems that may presently or with some degree of modification be used to manufacture products that comply with the proposed emission standards is discussed in the remainder of this chapter.

## 1. Legal Requirements

According to H&SC §39666, CARB is required to adopt ATCMs to reduce emissions of TACs. For TACs without a Board-specified threshold exposure level, H&SC §39666 requires the ATCM to be designed to reduce emissions to the lowest level achievable through the application of BACT, or a more effective control method. With respect to BACT for the present ATCM, there are two elements identified in H&SC §39665(a)(4) and §39665(a)(6) that need to be evaluated:

(4) The availability and technological feasibility of airborne toxic control measures to reduce or eliminate emissions, the anticipated effect of airborne toxic control measures on levels of exposure, and the degree to which proposed airborne toxic control measures are compatible with, or applicable to, recent technological improvements or other actions, which emitting sources have implemented or taken in the recent past to reduce emissions.

(6) The availability, suitability, and relative efficacy of substitute compounds of a less hazardous nature.

To determine BACT, staff evaluated the proposed control measure and alternatives to the proposed control measure by gathering pertinent information from a variety of sources, as described in the following subsections. For this ATCM, BACT is defined as HWPW, PB, and MDF meeting the proposed Phase 2 emission limits in Tables V-21, V-23, and V-25, respectively.

## 2. Best Available Control Technology Assessment Process

To ascertain BACT, staff collected information by exploring patents, scientific literature, consultations with academia, resin researchers and manufacturers, and examining the data collected in a CARB survey of composite wood products manufactured in 2002.

### a. Patents on Resins Used in Composite Wood Products

Staff researched the patents regarding resins used in composite wood products listed on the U.S. Patent & Trademark Office website (<http://www.uspto.gov/>) listed in 2001 through 2006, and found over 80 patents and 34 applications. Examples of resins included:

- Soybean flour and a cross-linking agent adhesive;
- Liquid melamine-urea-formaldehyde (MUF) resin that includes using a catalyst, thickener, and hardener;
- Water resistant polyvinyl acetate (PVA) aqueous emulsion;
- Tannin-based resins;
- Protein-modified urea-formaldehyde (UF) resin;

- Soy protein portion and modifying ingredient portion;
- Glutaraldehyde co-solvent urea resins;
- Formaldehyde-free lignocellulosic adhesive, and
- Hydrolyzates of soybeans as components of thermosetting resins.

b. Scientific Literature

Several search engines were used to locate articles in the peer-reviewed literature. The primary websites that were accessed include:

- Science Direct: lists handbooks, book series', and journal collections -- over 6.75 million articles;
- APT Online: lists current and archived journals, issues, and authors;
- Thomson Scientific: provides access to complete bibliographic information from over 8,000 leading journals and more than 2,000 books; and
- Google: enables users to search the web, usenet, and images.

c. Consultations

Through phone calls and emails, staff contacted resin researchers, resin manufacturers, and academia to discuss resin technology used in manufacturing composite wood products. Table V-1 lists the contacts made to date relative to resin technology.

Table V-1. List of Researchers, Manufacturers, and Academia Contacted	
Contact	Affiliation
Bailey, Mr. Chris	Collins Company (Portland, OR)
Gardner, Dr. Doug	University of Maine (Orono, ME)
Harmon, Dave	Hexion Specialty Chemicals (Springfield, OR)
Holloway, Tom	Dynea Adhesives (Springfield, OR)
Johns, Dr. William	Washington State University (Pullman, WA)
Kelly, Dr. Myron	North Carolina State University (Raleigh, NC)
Kim, Dr. Moon	Mississippi State University (Starkville, MS)
Li, Dr. Kaichang	Oregon State University (Corvallis, OR)
Matuana, Dr. Laurent	Michigan State University (East Lansing, MI)
Moriarty, Mr. Chris	Huntsman International, LLC (Salt Lake City, UT)
Odda, Mr. Ulf	Akzo Nobel (Sweden)
Pizzi, Dr. Antonio	ENSTIB, University of Nancy I FR (France)
Rosengarh, Mr. T.J.	Flakeboard Company, Ltd. (Canada)
Shupe, Dr. Todd	Louisiana Forest Prod. Dev. Ctr. (Baton Rouge, LA)
Sun, Dr. Susan	Kansas State University (Manhattan, KS)
Tang, Dr. R.C.	Auburn University (Auburn, AL)
Taylor, Mr. Mike	States Industries (Eugene, OR)
Wescott, Dr. James	Heartland Resource Technologies, LLC (Pasadena, CA)
Wolcott, Dr. Michael	Washington State University (Pullman, WA)

In conjunction with public workshops and stakeholder meetings held over the years, staff has also made contact with a number of U.S. and overseas manufacturers, including:

- Columbia Forest Products (Portland, OR)
- Flakeboard (Canada)
- Georgia-Pacific (Decatur, GA)
- Masisa (Chile)
- Roseburg Forest Products (Roseburg, OR)
- SierraPine, Ltd. (Roseville, CA)
- States Industries (Eugene, OR)
- Timber Products (Springfield, OR)
- Weyerhaeuser (Eugene, OR)

d. 2003 California Air Resources Board Survey

The CARB staff distributed a composite wood products survey to manufacturers across the U.S. in March 2003 to collect information regarding engineered wood products, such as plywood, particleboard, fiberboard, and other composite wood products. The survey, hereafter referred to as the “2003 CARB Survey”, consisted of four questionnaires pertaining to manufacturer, product, resin, and process information. Over 250 surveys were mailed out, in which respondents were asked to provide information pertaining to products manufactured in 2002. From the 250 surveys distributed, ARB received 57 responses. Staff categorized the responses by composite wood type and entered all information into an Access™ database.

Based on an analysis of the survey results, the highest formaldehyde-emitting composite wood products were hardwood plywood, particleboard, and medium density fiberboard for interior applications. The majority of these products are made with urea-formaldehyde resins, which are inexpensive, and emit more HCHO than products made with other resins. For this ATCM, controlling the HCHO emissions from hardwood plywood, particleboard, and medium density fiberboard was the focus of this BACT assessment.

### **3. Overview of Existing Formaldehyde Standards and Regulations**

During the 1970's, HCHO emissions from PB and HWPW led to numerous complaints in newly constructed homes. In 1985, the U.S. Housing and Urban Development Agency (HUD) implemented a regulation that limited the HCHO concentration in mobile homes to 0.4 parts per million (ppm) (Spelter, 1992). This would be achieved by lowering HCHO emissions from PB and HWPW to 0.3 and 0.2 ppm, respectively. This action triggered a need for many HWPW and PB manufacturers to modify their products in order to comply with the standard. However, absent any new regulations since 1985, industry has continued to

produce products that comply with the HUD standard (Turner et al., 1996) with modest reductions in average HCHO emissions. Products specifically covered under the HUD standard are not subject to the proposed ATCM.

Similar concerns relative to the health effects of HCHO emissions from composite wood products and HCHO in indoor air were also being raised in Europe. This led to a guideline from the German health ministry in 1980 to limit HCHO emissions from particleboards, fiberboards, and plywood to 0.1 ppm in a steady state climate chamber test, which is also known as the E1 classification (Deutsches Institut für Bautechnik, 1994). In 2000, Australia adopted the same standards as those used in Europe. Compliance with European regulations is based on the quantity of free-formaldehyde in a product rather than the actual emissions from the product; the presumption for this is that any free-formaldehyde in a wood product will be emitted at a later time. The E1 standard is an “average” standard that allows for panels to be produced with HCHO contents higher than the numerical value of the standard, so long as an equal amount of product is produced at a comparable HCHO content below the standard. In terms of HCHO contents, Europe allows multiple grades of panels to be sold for consumer use. As such, not all panels sold to Europe meet the E1 standard; a portion is made to comply with the E2 standard, which approximates the stringency of the 1985 HUD standards in the U.S.

The most stringent HCHO regulation implemented today is the Japanese Building Standard Law (BSL) (Takabatake, 2003). The BSL has a “sick house” regulation which regulates the amount of chemical products, such as HCHO, that can be emitted from building materials. As noted above for Europe, multiple grades of products are allowed in Japan, in terms of HCHO content. There are 15 kinds of HCHO-emitting building materials subject to the regulation, which include plywood, PB, and MDF. The regulation requires suppliers of building materials to determine HCHO emission levels from their products and comply with applicable JIS (Japan Industrial Standards) or JAS (Japan Agriculture Standards), or obtain approval from the Ministry of Land, Infrastructure and Transport (MLIT). All building materials are classified by HCHO emission rate into four formaldehyde-emitting categories: Type I, F☆☆, F☆☆☆, and F☆☆☆☆. Table V-2 describes the four Japanese formaldehyde-emission standards for building materials. The emission standards are expressed as an emission rate as determined by testing with the Japanese desiccator test.

Table V-2. Japanese Building Standard Law Classifications for Building Material Formaldehyde (HCHO) Emissions<sup>1</sup>

Classification	HCHO Emission Rate (mg/m <sup>2</sup> /hr)	Board Usage
Type I	$0.12 < x$	Prohibited in use
F☆☆	$0.02 < x \leq 0.12$	Tighter area restriction
F☆☆☆	$0.005 < x \leq 0.02$	Area restriction
F☆☆☆☆	$x < 0.005$	No restrictions

(<sup>1</sup>) Source: Takabatake (2003). “mg/m<sup>2</sup>/hr” = milligrams HCHO per square meter per hour.

The use of Type 1 building materials as interior finishing materials in habitable rooms is prohibited. The use of F☆☆ and F☆☆☆ building materials in habitable rooms is limited, depending on total area of the room(s). The amount of F☆☆ and F☆☆☆ building materials is adjusted based on the number of ventilators and floor area of each habitable room. Use of F☆☆☆☆ building materials is without any limitations.

To meet these demanding HCHO standards, resins must be modified to reduce HCHO emissions levels to a significant extent. Low HCHO resins have been developed by engaging one or more technological methods, such as:

- Lowering the formaldehyde:urea (F:U) ratio of the UF resin;
- Adding formaldehyde-scavenger materials directly to the UF resin;
- Post-treating panels with a formaldehyde scavenger; or
- Changing to a new resin system.

From this list of options, the primary method used to decrease HCHO emissions is by lowering the F:U ratio. In the 1980’s, F:U ratios were generally between 1.4 to 1.6. Today, F:U ratios in resins used in the U.S. range from 1.05 to 1.2 (Bauman, 1997). To an extent, the results of the CARB 2003 survey suggest that more stringent HCHO emission standards in Europe and Japan have prompted U.S. manufacturers to lower the F:U ratios in the resins that they use. Some UF resins with F:U ratios of 0.8 to 0.9 have been developed. However, complications in the mechanical and physical performance of wood panels may arise when HCHO levels are lowered. This is usually compensated for by adding a substitute compound in place of HCHO, or by fortification with chemicals intended to reinforce the glue bonds.

Another option to significantly lower HCHO emissions is adding HCHO scavengers directly to UF resins before press time. These scavengers are usually nitrogen-based compounds that bind to free-formaldehyde in the resin. Urea scavengers have been used for many years and are very effective in reducing HCHO emissions without influencing the physical characteristics of the

wood panel. Another type of scavenger is a scavenger wax emulsion, which reduces HCHO emissions in two ways: it scavenges free-formaldehyde and also hinders water absorption by the wood panel. Most HCHO scavengers are cost effective and widely used in North American plants.

There are also a variety of post-pressing board treatments used to reduce HCHO emissions from UF resins (Myers, 1986). While post-pressing treatments are used to a lesser extent than pre-pressing treatments, both are very effective. The most common post-pressing treatment used to reduce HCHO emissions is to fumigate wood panels with anhydrous ammonia. Significant HCHO emission reductions, two to 10 times less, can be achieved by exposure to anhydrous ammonia. Other post-press treatments include adding liquid ammonia or ammonia salt solutions to the board surface. Ammonium bicarbonate and ammonium carbonate have been used as solid powders, while solutions of ammonium salts, alkali metal salts, and other compounds having amine functionality have been found to be effective.

Breakthroughs in resin chemistry have led to the development of new resin systems that are either low-emitting or zero-added HCHO, to meet the more stringent European E1 and Japan F☆☆☆☆ standards. Table V-3 compares the different HCHO emission standards for composite wood products in the U.S., Europe, and Japan. In the U.S., separate standards are established for PB, plywood, and MDF (i.e., voluntary standards set by ANSI) based on surface HCHO emissions (ASTM E1333). In Europe, the standards for PB and plywood are based on surface HCHO emissions (EN 717-1), but compliance with the standard is determined by the amount of free-formaldehyde in PB (EN 120) or by the HCHO emission rate in plywood (EN 717-2). In Japan, all building materials subject to the Building Standard Law are based on HCHO emission rate (JIS A1901). Because these various standards are applied differently, target different health related goals, and tested using different analytical methods, they are not directly comparable to the proposed Phase 1 and Phase 2 standards developed by staff. An analysis of the relative stringency of the standards in the proposed ATCM is contained in Appendix H. In Appendix H, the approximate ASTM E1333-equivalent values for E1 products are estimated to be 0.14 ppm for HWPW and PB, and 0.10 ppm for MDF. For the F☆☆ and F☆☆☆, the approximate ASTM E1333-equivalent values are estimated to be 0.07 and 0.04 ppm, respectively.

Table V-3. Formaldehyde (HCHO) Emission Standards for Composite Wood Products in the U.S., Europe, and Japan <sup>1</sup>			
Standard	Product	HCHO Limit	Test Method
U.S.	Particleboard	0.30 ppm	ASTM E1333
	Med. Density Fiberboard	0.30 ppm	
	Plywood Wall Panels	0.20 ppm	
	Industrial Plywood	0.30 ppm	
Europe – E1	Particleboard, Plywood	0.10 ppm	EN 717-1
	Particleboard	6 to 10 mg/100 g	EN 120
	Plywood	≤ 3.5 mg/m <sup>2</sup> /hr	EN 717-2
Japan – F Standards	All Products -- F☆☆	0.02 to 0.12 mg/m <sup>2</sup> /hr	JIS A1901
	All Products -- F☆☆☆	0.005 to 0.02 mg/m <sup>2</sup> /hr	
	All Products -- F☆☆☆☆	≤ 0.005 mg/m <sup>2</sup> /hr	

(<sup>1</sup>) Sources: ASTM (1996); Building Center of Japan (2004); Groah et al. (1991); National Particleboard Association (1994). The U.S. standard for MDF is the voluntary ANSI standard. "ANSI" = American National Standards Institute; "ppm" = parts per million; "mg/100g" = milligrams per 100 grams of dry board; "mg/m<sup>2</sup>/hr" = milligrams per square meter per hour; "ASTM E1333" = American Large Chamber Test Method; "EN 717-1" = European Institute Large Chamber Test Method; "EN 120" = European Perforator Test; "EN 717-2" = European Gas Analysis Method; "JIS A1901" = Japanese Small Chamber Test.

## B. Product Descriptions and Survey Results

This section provides information on how the selected products are manufactured, the results of analyses of the "CARB 2003 Survey," and for HWPW, an evaluation of supplemental data submitted by the Hardwood Plywood & Veneer Association to CARB.

### 1. Hardwood Plywood

#### a. Description and Properties

Hardwood plywood (HWPW) consists of thin wood veneers (or plies) glued together so that the grain direction of each layer of veneer is perpendicular to that of its adjacent layers (Youngquist, 1999). This cross-lamination provides excellent two-way strength for a suite of stiffness (e.g., dry shear test) and water resistance properties (e.g., three-cycle soak test) (American National Standards Institute, 2000). Hardwood plywood is always constructed with an odd number of plies, where the outside and inside plies are referred to as the faces and core,

respectively. There are several types of HWPW differentiated by the thickness and composition of the core, which is commonly made with either veneer, lumber, MDF, or PB. The outermost layer or face layer is finely finished wood surface made from a hardwood species such as oak or maple.

With respect to water resistance, there are four grades of HWPW: Technical, Type I, Type II, and Type III, where Technical grade HWPW is the most water-resistant and Type III the least (Youngquist, 1999). To our knowledge, in order to produce HWPW for exterior applications (i.e., Technical or Type 1), resins other than urea-formaldehyde (UF) resins are used (e.g., phenol-formaldehyde), which typically have HCHO emission rates that are 90% or more below that of HWPW made with a UF resin (Battelle, 1996). In comparison, HWPW designated as either Type II or III are interior-grade products that are largely used as decorative wall paneling, and the construction of cabinets and furniture (Norbord Inc., Not Dated). The resin most commonly used in these products is UF resin, which has been found to produce HWPW with ASTM E1333 values ranging from 0.05 to 0.19 ppm (Hardwood Plywood & Veneer Association, 2006).

b. Analysis of Responses to the CARB 2003 Survey

To learn more about the HCHO emission characteristics of HWPW produced in the U.S., a survey (CARB, 2003) was mailed to domestic manufacturers. The intent of the CARB 2003 Survey was to learn about the types of equipment used to manufacture composite wood products and to determine the characteristics of HWPW, PB, and MDF produced in the U.S. in 2002. A total of 10 responses were received with information on HWPW, representing approximately 73% of total U.S. production (in 2002, total U.S. production was estimated to be approximately  $1.5 \times 10^9$  ft<sup>2</sup>, based on  $\frac{3}{8}$ " thickness). The range of reported ASTM E1333 values from the 10 respondents was 0.07 to 0.75 ppm, and the production-weighted grand mean was 0.09 ppm. All 10 companies reported using an ammonia-UF resin to manufacture their HWPW, where the lowest ASTM E1333 values were achieved by manufacturers that added catalysts (e.g., ammonium chloride or hexamethylenetetramine (hexamine)). The HWPW that was reported to have an ASTM E1333 value of 0.75 ppm was an architectural plywood product, which is produced in very low volumes for highly specialized applications (e.g., curved objects).

c. Supplemental Data from the Hardwood Plywood & Veneer Association

In fall 2006, various stakeholders in the HWPW industry asked if consideration had been given to establishing separate HCHO emission standards for HWPW made with a veneer core (HWPW-VC) vs. HWPW made with a composite core (HWPW-CC) (i.e., core material is either PB or MDF). As this distinction had not been specified previously, there were no plans at the time to establish separate standards for the two products. To clarify the need for separate standards and to supplement analyses of the CARB 2003 Survey data, the Hardwood Plywood &

Veneer Association (HPVA) offered to submit HCHO emission data from HWPW-VC and HWPW-CC manufactured in 2001-06 from several companies (Note: Statutes governing manufacturer confidentiality prohibit the disclosure of actual company names). The HCHO emission data for HWPW-VC from six companies, measured using either ASTM D5582 (desiccator test) or ASTM E1333 (large chamber test) were provided for two to five years of production (Table V-4).

Table V-4. Measured or Estimated ASTM E1333 Average Data for Hardwood Plywood-Veneer Core from Selected U.S. Manufacturers <sup>1</sup>			
Company	Year	No. Samples	ASTM E1333 (ppm)
HPVA #1	2004-05	20	0.12
HPVA #2	2001-05	40	0.13
HPVA #3	N/A	11	0.10*
HPVA #4 – Mill F	2003-05	18	0.12*
HPVA #4 – Mill G	2001-05	56	0.09*
HPVA #4 – Mill H	2001-04	15	0.09*
HPVA #4 – Mill I	2001-05	103	0.13*
HPVA #4 – Mill J	2004-05	6	0.15*
HPVA #5 – Mill A	2001-05	6	0.17
HPVA #5 – Mill B	“	11	0.08
HPVA #5 – Mill C	“	16	0.09
HPVA #5 – Mill D	“	6	0.19
HPVA #5 – Mill E	“	9	0.10
HPVA #6	2004-06	32	0.09
Grand Mean (n = 14)	-----	-----	0.12

(<sup>1</sup>) Data provided by the Hardwood Plywood & Veneer Association; ASTM E1333 data followed by an asterisk indicate values estimated by multiplying measured ASTM D5582 data by 0.4.

In consideration of the variation in numbers of samples, reported years, and company/mill information, multiple-year means were calculated for each mill that could be identified. For data that could not be assigned to a specific mill, data for the entire company were averaged. In 2001-06, facility mean ASTM E1333 values ranged from 0.09 to 0.19 ppm, and the grand mean was 0.12 ppm (n = 14). Relative to the data from the CARB 2003 Survey, the range of reported ASTM E1333 values was smaller, but the grand mean was 25% higher (i.e., 0.12 ppm vs. 0.09 ppm in the CARB 2003 Survey).

Less data were provided for HWPW-CC (i.e., three companies vs. six for HWPW-VC) (Table V-5), which in part reflects lower production volumes for HWPW-CC than HWPW-VC. As for the HWPW-VC data, multiple-year means were calculated for each company, and the company means averaged to calculate a grand mean. Compared to HWPW-VC, the range in ASTM E1333 values was

smaller, as was the grand mean (0.08 ppm for HWPW-CC vs. 0.12 for HWPW-VC), which may have been influenced by the difference in sample sizes. These data, in light of the lower grand mean and inter-company range in ASTM E1333 values for HWPW-CC, does not support the need for emission standards with different ASTM E1333 values for HWPW-VC and HWPW-CC at this time.

Table V-5. Measured or Estimated ASTM E1333 Data for Hardwood Plywood-Composite Core from Selected U.S. Manufacturers <sup>1</sup>				
Company	Core	Year	No. Samples	ASTM E1333 (ppm)
HPVA "A"	PB	2005	1	0.05
HPVA "B"	PB	2001-04	11	0.08
HPVA "C"	PB	NA	8	0.10*
HPVA "B"	MDF	2001-03	5	0.09
HPVA "C"	MDF	NA	9	0.09*
Grand Mean (n = 5)	-----	-----	-----	0.08

(<sup>1</sup>) Data provided by the Hardwood Plywood & Veneer Association; ASTM E1333 data with an asterisk indicate values estimated by multiplying ASTM D5582 data by 0.4. NA = not available.

## 2. Particleboard

### a. Description and Properties

Particleboard is made of wood fragments, such as chips or shavings, that are dried and mechanically pressed with heat into sheet form, and bonded together with resin (Youngquist, 1999). There are typically three layers in a PB panel -- the two outer faces of the board, which consist of finely ground wood particles,

and the core which consists of more coarse material. Particleboard (85% or more) is used for furniture, flooring systems, underlayment, manufactured housing, and other products in conventional homes (e.g., cabinets) (Milton, 2006).

### b. Analysis of Responses to the CARB 2003 Survey

A total of 20 responses were received with information on PB, representing approximately 53% of total U.S. production (in 2002, total U.S. production was estimated to be approximately  $2.9 \times 10^9$  ft<sup>2</sup>, based on ¾" thickness). The range of reported ASTM E1333 values from the 20 respondents was 0.13 to 0.24 ppm, and the production-weighted grand mean was 0.18 ppm. In all, the 20 respondents reported using two UF and one phenol-formaldehyde (PF) resin to manufacture the products they offered for sale in 2002. One of the UF resins, used in approximately 51% of reported production volume, was a straight UF

polymer with a F:U mole ratio of 1.1 to 1.3 (Note: For UF resins, the mole amount of HCHO is typically greater than for urea. As such, if a UF resin is reported to have a mole ratio greater than 1, this reflects the F:U mole ratio and not the U:F mole ratio).

To reduce surface emissions of HCHO from PB made with a UF resin of this kind, manufacturers may include one or more additives to the resin such as catalysts (sodium chloride, sodium sulfate, ammonium sulfate), scavengers (low mole ratio urea solution), and/or wax emulsions (for moisture retention). The other UF resin was a methanol-UF resin that was used to produce approximately 48% of the reported volume of production. As for the straight polymer UF resin, surface emissions of HCHO may be reduced by use of the same additives mentioned above, as well as magnesium chloride-hexahydrate. The remaining 1% of reported production was manufactured with a blended PF-UF resin.

### **3. Medium Density Fiberboard (MDF)**

#### **a. Description and Properties**

Medium density fiberboard (MDF) is made of wood fibers and has stronger physical properties than PB (Youngquist, 1999). Fiberboard is classified by board density -- MDF has a specific gravity of 0.5 to 0.8 or a density of 31 to 50 lbs/ft<sup>3</sup> (Keidel Supply Co., Inc., 2001-06). The surfaces of MDF are smooth, uniform, and free of knots, and it can undergo a variety of finishing steps depending on the final product. The primary uses for MDF include furniture, cabinets, molding, door skins, and industrial packaging (Mithra, 2007).

#### **b. Analysis of Responses to the CARB 2003 Survey**

A total of 12 responses were received with information on MDF, representing approximately 83% of total U.S. production (in 2002, total U.S. production was estimated to be approximately  $1.6 \times 10^9$  ft<sup>2</sup>, based on ¾" thickness). The range of reported ASTM E1333 values from the 12 respondents was 0.03 to 0.31 ppm, and the production-weighted grand mean was 0.25 ppm. In all, the 12 respondents reported using three UF and one methylene diisocyanate (MDI) resin to manufacture the products offered for sale in 2002. Similar to PB, a major portion of manufacturers reported using a straight polymer UF (approximately 40% of reported production) or methanol-UF resin (approximately 20%), while others used a melamine-UF resin (approximately 39%) with sodium chloride as a catalyst. Although the same additives listed for PB may be used to control surface emissions of HCHO from MDF (i.e., catalysts, scavengers, and wax emulsions), the specific additives used to manufacture MDF are considered to be proprietary information. Of the reported volume of production, approximately 1% was made using a MDI resin.

## **C. Present-day Resin Technologies**

In this BACT assessment of present-day resin technologies, an evaluation of currently used and laboratory tested resins, and production processes that may be used to achieve the maximum feasible HCHO emission reductions from HWPW, PB, and MDF was conducted. Staff's review of the literature concludes that generally speaking, resin technologies can be applied to all three regulated products (HWPW, PB, and MDF), although adjustments in resins may be necessary to accommodate the different manufacturing processes. In addition, the assessment also considers the results of the CARB 2003 Survey, patent searches, a literature review, and consultations with resin suppliers, panel manufacturers, and academia. In this analysis, resin systems were evaluated in consideration of the need to meet selected structural properties.

### **1. Urea-formaldehyde (UF) Resins**

Presently, UF resins are the most widely used adhesives in the manufacture of HWPW, PB, and MDF, which produces boards with the highest HCHO surface emissions (i.e., ASTM E1333 values). The basic chemical reaction in UF resins involves bond formation between amine and hydroxyl groups on the resin components. New technologies seek to find alternative components that are able to form irreversible bonds with HCHO to reduce the amount of free HCHO that remains in the final product. To produce HWPW, PB, and MDF with a UF resin that would achieve lower HCHO emissions, manufacturers may choose to use resins with lower F:U mole ratios (i.e., less than 1.0), add different amounts or mixtures of scavengers and hardeners, and/or apply decreased press times and temperatures (Wolcott et al., 1996). Limited studies indicate the potential to meet the F☆☆☆☆ standards, but it is not clear as to how low an ASTM E1333 value can be achieved using a UF resin, as efforts made to date to lower surface HCHO emissions from HWPW, PB, and MDF are not well documented in the open literature.

### **2. Melamine-urea-formaldehyde (MUF) Resins**

The most widely used approach for decreasing surface HCHO emissions from boards made with a UF resin is to lower the F:U mole ratio of the base resin. Presently, mole ratios are reported to range from 1.05 to 1.2, depending on the specific formulation of the resin (Baumann, 1997). However, when the F:U mole ratio is lowered below 1.0 (i.e., more moles of urea than HCHO), adjustments must be made to the resin to moderate unwanted changes in the physical and structural properties of the board. The addition of melamine during resin synthesis is often used to improve the durability and stability of a board, and its addition can also decrease surface HCHO emissions by acting as cross-linking agent.

Cremonini and Pizzi (1999) measured the effects of adding melamine acetate (Mac) on the tensile strength of plywood made with a UF resin (F:U mole ratio =

1.5). Measurements of tensile strength were made before and two-years after exposure to the weather in northern Italy (Table V-6). While plywood made with a “UF + 15% Mac” resin had a lower initial tensile strength than plywood made with commercially available Phenol-MUF resin, it had a higher tensile strength after two-years of weather exposure (1.27 vs. 1.05 N/mm<sup>2</sup>). In comparison, plywood made with commercially available MUF resin exhibited both higher initial and post-exposure tensile strength than plywood made with PMUF or any “UF + Mac” resin combinations. Overall, the durability of plywood made with 15% or more Mac would allow manufacturers to produce panels that comply with European tensile strength requirements, comparable to plywood made with a MUF resin with 33 to 40% melamine. This suggests that the addition of Mac to UF resins may be equally as effective in maintaining plywood tensile strength as MUF resins with higher melamine contents. Pizzi (2000) also reported that equivalent tensile strengths were measured in plywood bonded with a 40:60 weight ratio MUF resin and plywood bonded with a 10:90 weight ratio melamine-salt UF resin.

Table V-6. Effect of Melamine Acetate (Mac) on Plywood Tensile Strength <sup>1</sup>		
Resin (M:U weight ratio)	----- Tensile Strength (N/mm <sup>2</sup> ) -----	
	Initial	Post-exposure
PMUF Control (33:66)	1.48	1.05
MUF Control (47:53)	2.07	1.91
UF + 10% Mac (7:93)	0.52	0
UF + 15% Mac (10:90)	1.33	1.27
UF + 20% Mac (13:87)	1.10	1.07
EN 314 Requirement	> 1.0	NA

<sup>(1)</sup> Source: Cremonini and Pizzi (1999). PMUF = phenol melamine urea-formaldehyde; MUF = melamine urea-formaldehyde; UF = urea-formaldehyde. The base UF resin had a F:U mole ratio of 1.5. Post-exposure tensile strength is the value after two-years of weather-exposure in northern Italy. NA = not applicable.

Relative to lowering HCHO emissions, Dunky (1995) developed a MUF resin using a very low mole ratio UF resin (F:U = 0.75 to 0.90) and adding 15 to 23% melamine by weight to achieve very low HCHO concentrations. With respect to HCHO content, the panels exhibited DIN EN 120 values less than 2.0 mg/100 g (approximate ATSM E1333 value of 0.025 ppm).

Akzo Nobel (2005; 2006) is currently conducting laboratory trials on a MUF resin made with a low mole ratio UF resin (F:U = 1.05 to 1.15), melamine, and a “catcher” compound. The catcher is specifically formulated to decrease HCHO emissions from PB produced with the MUF resin. Particleboard, ranging in thickness from 16 to 28 mm, has been produced at a press temperature of 185 °C and a 10.8 s/mm press time. While the resin system is still in laboratory trials, it has shown good success in terms of producing PB with low JIS A1460 (Japanese desiccator test) values (less than 0.3 mg/L ≈ ASTM E1333 value of

0.04 ppm) and improving durability when applied at a 10% by weight resin dosage. This resin system has the potential to be used to make PB with very low HCHO emissions.

### **3. Melamine-formaldehyde (MF) Resins**

Melamine-formaldehyde resins are excellent exterior wood adhesives because of their water resistance. Frihart and Chandler (2006) found that MF resins could reduce wood swelling by entering into the walls of wood cells and strengthening them.

Kim and Kim (2005) conducted a range of HCHO emission tests (e.g., DIN EN 120, JIS A1460) on 8-mm MDF made from Korean pine (4% moisture content) and bonded with a MF resin. The resin had a F:M mole ratio of 1.75. Before the MDF was pressed, three-parts (to resin) of 25% ammonium chloride (hardener) and 13 parts of 44% wax solution (for waterproofing) were added to the base MF resin. The MDF made with the MF resin displayed a JIS A1460 value of 0.6 ppm and a DIN EN 120 value of 2.88 mg/100 g dry board, which complies with the Japanese F☆☆ and nearly the F☆☆☆☆ standard.

Pizzi et al. (1996) examined the strength and HCHO emission properties of PB made under laboratory conditions with either a 0.5 or 1.1 mole ratio MF resin containing ammonium chloride (i.e., 15-parts by weight of a 20% solution). Hexamine (i.e., 38-parts by weight of a 40% solution) was added to the 0.5 mole ratio MF resin to determine if hexamine addition could compensate for the resin's lower melamine content. Observed differences in dry internal bond strength and DIN EN 120 results are shown in Table V-7 for PB made with the two MF resins. These results confirm that the addition of hexamine to a low mole ratio MF resin allows for the production of PB with similar internal bond strengths as PB made with higher mole ratio MF resins. In addition, the DIN EN 120 value of the PB made with the hexamine-hardened MF resin was approximately 50% lower than the value of the higher mole ratio MF resin without hexamine. Overall, it appears that adding hexamine as a hardener to MF resins may be an effective way to lower HCHO emissions and maintain internal bond strength in PB. Further research is needed to identify the optimal amount of hexamine to add to MF resins for the manufacture of PB with acceptable internal bond strengths and low HCHO emissions.

The findings from these studies demonstrate the potential for using MF resins to produce PB or MDF with low HCHO emission properties.

Table V-7. Comparison of Strength and HCHO Emission Properties of Particleboard Made with Two Melamine-formaldehyde (MF) Resins <sup>1</sup>		
Resin or Particleboard Parameter	----- Resin -----	
	MF Alone	MF + Hexamine
MF Mole Ratio (Parts by Weight)	1.1 (174)	0.5 (154)
Dry Internal Bond Pressure (MPa)	0.77	0.65
DIN EN 120 (mg HCHO/100 g)	6.9	3.5

<sup>(1)</sup> Source: Pizzi et al. (1996). MPa = megapascals; mg = milligrams; g = grams. DIN EN 120 refers to the European perforator test. The press time for PB made with either resin was 4-minutes.

#### 4. Phenol-formaldehyde (PF) Resins

Phenol-formaldehyde resins are commonly used in PB for exterior applications that must be durable under wet and/or humid conditions. They typically exhibit low HCHO emission rates (Battelle, 1996), and selected commercially available products would likely comply with the proposed Phase 2 standards that would take affect in 2011 to 2012 (Appendix A). Industry representatives have expressed concern over the longer press times and higher press temperatures required for producing products with PF versus UF resins, as these changes result in higher energy consumption and decreased productivity. However, recent studies have shown that adding compounds such as esters, lactones, or organic carbonates to PF resins can reduce cure times (Conner et al., 2002; Lorenz and Conner, 2000; Pizzi et al., 1997).

#### 5. Methylene Diisocyanate (MDI) Resins

Since the 1970's, MDI has been increasingly used in the manufacture of MDF (Eckelman, 1997). As a non-polar, low viscosity liquid that wets the wood surface and penetrates deep into the wood structure, MDI resins penetrate further than PF resins, thus creating one of the most durable adhesive networks. While more expensive than any other resin discussed in this section, there are no HCHO emissions associated with its use, enabling PB and MDF made with this adhesive to meet the proposed Phase 2 standards that would take effect in 2011 to 2012. A number of other properties that make MDI a desirable adhesive for composite wood products include:

- Fast polymerization rate (making it suitable for use as core resin) and ability to form bonds with wood with a high moisture content, including green wood (Connor, 2001; Frihart, 2005);
- Low volatility – less resin is used to manufacture products with comparable structural properties (Marra, 1992); and

- Lower energy-related production costs due to the use of lower press temperatures, faster press cycles, and shorter drying times (Connor, 2001).

At the industrial-scale, research on isocyanates is presently focused on their use as a copolymerization agent in existing resins, which have led to the creation of hybrid resin systems (e.g., UF-MDI, PF-MDI, PUF-MDI, PMUF-MDI, and PUFT-MDI) that outperform traditional wood resins (Lei et al., 2006).

## **6. Methylene Diisocyanate (MDI) Hybrid Resins**

### **a. Urea-formaldehyde-MDI (UF-MDI) Resins**

Composite wood products made with UF resins are only used for interior applications because they have very low water resistance properties. However, researchers working with MDI hybrids have recently created an exterior-grade UF-MDI hybrid resin for use in a range of applications (Mansouri et al., 2006). By using a UF-MDI resin made by adding MDI (10 to 15% by weight) to a UF resin, the water resistance of plywood was substantially upgraded. Wieland et al. (2006) found that adding ammonium sulfate (approximately 2% by weight) could further accelerate plywood curing times. In plywood, the strength of the bond-lines made with a UF/MDI hybrid resin are much improved relative to those made with a UF resin due to the greater number of urethane crosslinks that form between isocyanate and UF methylol groups.

Mansouri et al. (2006) examined the changes to structural properties in plywood made with UF-MDI hybrid resins ranging from 5 to 15% MDI by weight (Table V-8). The test material was a three-layer beech veneer plywood bonded with a base UF resin (F:U mole ratio = 1.6 to 1.8) that was modified by the addition of ammonium sulfate (2% solution), wheat flour (30% by weight), and MDI. The results show that as the amount of MDI is increased, the boiling water performance of the plywood improved (e.g., after 11-minutes the tensile strength of the control was four- to five-times lower than the plywood made with any of the UF-MDI hybrid resins). While the selected measures of tensile strength were all improved by the addition of MDI to the UF resin, the extent of improvement is much greater when 10 to 15% MDI is added vs. only 5%. To produce plywood with exterior-grade properties using a UF resin, greater amounts of MDI would need to be added to achieve the required level of water resistance. Nevertheless, the tensile strength and water resistance properties of plywood made with a UF resin can be considerably improved by the addition of 10 to 15% MDI by weight.

Table V-8. Selected Measures of Tensile Strength (N/mm<sup>2</sup>) in Plywood Made with Urea-formaldehyde (UF) and UF-Methylene Diisocyanate (UF-MDI) Hybrid Resins<sup>1</sup>

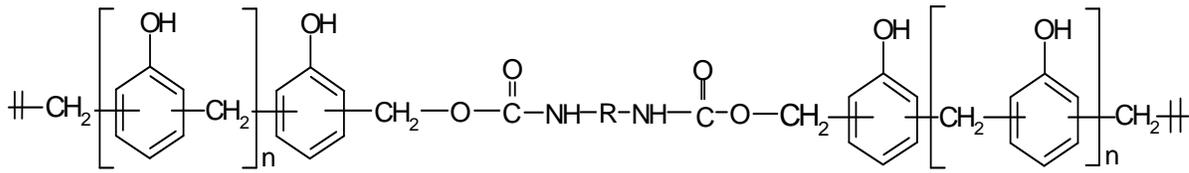
Test	----- Tensile Strength (N/mm <sup>2</sup> ) -----			
	UF	UF-MDI (5%)	UF-MDI (10%)	UF-MDI (15%)
Dry Internal Bond	2.00	2.07	2.13	1.89
24-hour Cold Soak	1.91	2.00	2.00	2.26
Boiling Water: 3-min	2.27	2.88	2.49	2.57
Boiling Water: 5-min	1.96	2.41	2.52	2.32
Boiling Water: 7-min	1.87	2.02	2.21	2.18
Boiling Water: 11-min	0.42	1.84	1.70	1.90
Boiling Water: 15-min	0	0	1.28	1.95
Boiling Water: 19-min	0	0	1.25	1.49
Boiling Water: 23-min	0	0	0	0.71
Boiling Water: 27-min	0	0	0	0.61
Boiling Water: 30-min	0	0	0	0

<sup>(1)</sup> Source: Mansouri et al. (2006). For the UF-MDI headings, values in parentheses indicate the amount of MDI in the resin on a weight-basis. "min" = minutes. Glue-spread = 300-320 g/m<sup>2</sup>; press time = 5 min; press temperature = 120 °C; press pressure = 11 kg/cm<sup>2</sup>.

b. Phenol-formaldehyde-MDI (PF-MDI) Resins

Phenol-formaldehyde and MDI resins have been used to manufacture plywood and oriented strand board (OSB) for exterior applications outside the U.S. because of their excellent water resistance. Presently, PF resins dominate the market for exterior and marine-grade plywood (Pizzi et al., 1995); however, PF resins are less effective when used to bind wood veneers with high moisture contents. This limitation may be overcome by adding MDI to a PF resin (as in a PF-MDI hybrid), as it raises the moisture tolerance of the resin, promotes resin curing, and enables a stronger bond-line to develop between the plywood veneers (Figure V-1). When used alone, full curing of a MDI resin requires veneer moisture contents to be above 10% and curing time is not affected until the veneer moisture content is greater than 18% (Zheng, 2002). Compared to PF resins, MDI resins have a faster cure rate at lower press temperature and better resin network stability at lower adhesive spread levels (Conner, 2001), and are currently used in industrial applications to upgrade the performance of traditional wood resins (Lei et al., 2006).

Figure V-1. Polyurethane Cross-linking in a PF-MDI Hybrid Resin



c. Phenol-urea-formaldehyde-MDI (PUF-MDI) Resins

Phenol-urea-formaldehyde (PUF) resins have been used for exterior applications since the early 1990's (Pizzi, 1994). To reduce resin cost, increasing amounts of urea have been added, which affects a number of structural properties in PB, especially water resistance (Osman et al., 2005). To counterbalance the effects of urea, MDI can be added to improve the performance of the board and to accelerate the curing process.

Table V-9. Effect of MDI and/or Urea Additions on Selected Resin and Panel Properties in Particleboard Made with Phenol-urea-formaldehyde (PUF) Resins<sup>1</sup>

Resin or Panel Property	----- PUF Resin -----			
	Control	10% MDI	10% MDI + 15% Urea	10% MDI + 20% Urea
Viscosity (MPa · s)	570	570	210	164
Board Density (kg/m <sup>3</sup> )	693	706	708	705
Wet Internal Bond (MPa)	0.16	0.25	0.19	0.16

<sup>(1)</sup> Source: Osman et al. (2005). "MPa · s" = megapascals-second; "g/cm<sup>3</sup>" = grams per cubic centimeter; "MPa" = megapascals. Particleboard press temperature = 195°C, press time = 11 s/mm, and pressure = 28 kg/cm<sup>2</sup>. Wet internal bond strength was measured after the PB was boiled in water for two-hours and dried for 16-hours (DIN 68763).

Osman et al. (2005) examined the properties of 16-mm PB made with four PUF resins, to evaluate the changes resulting from additions of MDI and urea. The control PUF resin had a solids content of 59% and contained approximately 40% urea by weight. The test resins were "PUF + 10% MDI," "PUF + 10% MDI + 15% urea," and "PUF + 10% MDI + 20% urea." With respect to resin viscosity, addition of MDI alone had no effect relative to the PUF control, but urea additions resulted in sizable reductions (Table V-9). While only minor changes were observed in PB density (i.e., 1 to 2% higher than the PUF control), the addition of 10% MDI to the PUF resin dramatically increased the wet internal bond strength

of PB compared to the PUF control, except with addition of 20% urea. With further research, it is conceivable that a cost-competitive PUF-MDI hybrid resin may be developed to allow manufacturers to produce PB with the desired structural properties and low HCHO surface emissions.

d. Phenol-melamine-urea-formaldehyde-MDI (PMUF-MDI) Resins

Phenol-melamine-urea-formaldehyde (PMUF) resin is used to manufacture exterior-grade composite wood panels. The resin is made by co-reaction of a PMUF resin with 5 to 10% phenol (Cremonini et al., 1996).

Lei et al. (2006) evaluated the effects of adding small increments of MDI to a PMUF resin on PB performance. The base PMUF resin had P:M:U:F mole ratio of 0.11 phenol, 0.33 melamine, 1.18 urea, and 2.15 formaldehyde, plus ammonium sulfate (3% by weight). Small additions of MDI did not appear to affect PB dry internal bond strength, as the value for PB made with 100% MDI was only 14% higher than for the PB made with 100% PMUF resin (Table V-10).

Table V-10. Dry and Wet Internal Bond (IB) Strength and Density in Particleboard Made Phenol-melamine-urea-formaldehyde (PMUF)-MDI Resins <sup>1</sup>				
PMUF Resin	----- Internal Bond (IB) or Density -----			
% MDI Added	Dry IB (MPa)	Dry Density (kg/m <sup>3</sup> )	Wet IB (MPa)	Wet Density (kg/m <sup>3</sup> )
0	1.00	711	0.09	727
5	0.95	693	0.21	675
10	1.05	726	0.23	713
15	1.08	697	0.29	720
25	0.94	701	0.46	714
50	1.00	702	0.48	694
75	1.01	702	0.46	689
85	1.02	681	0.36	708
90	1.05	698	0.45	674
95	0.98	681	0.48	700
100	1.14	653	0.58	660

<sup>(1)</sup> Source: Lei et al. (2006). "MPa" = megapascals; "kg/m<sup>3</sup>" = kilograms per cubic meter. The total resin solid content of the PB was 10%. Particleboard press temperature = 195 °C, press time = 11 s/mm, and maximum pressure = 33 kg/cm<sup>2</sup>. Wet internal bond strength was measured after the PB was boiled in water for two-hours and dried for 16-hours.

Far greater changes were observed in wet internal bond strength where additions of 5 or 10% MDI raised values by more than two fold (i.e., 0.21 to 0.23 vs. 0.09 MPa). When the amount of MDI was 25% or more, wet internal bond strength was increased by four or five fold relative to the PMUF control. Densities of the

PB ranged from 653 to 727 kg/m<sup>3</sup> in measurements made before or after the wet internal bond test. While lower densities were measured in PB made with 85% or more MDI before the wet internal bond test, the reductions were not consistently observed after the wet internal bond test. At lower MDI additions (e.g., 10 to 25%), PB density appeared to be consistently higher relative to PB made with the PMUF resin without added MDI. In conclusion, as for the other MDI hybrid resins discussed previously (e.g., UF-MDI, PF-MDI, PUF-MDI) adding small amounts of MDI to a PMUF resin was also found to dramatically increase the performance of PB. For PMUF resins, the largest improvement was observed for wet internal bond strength, where additions of 5 to 10% MDI are likely to result in only a small increase in resin cost.

#### **D. Candidate Low-formaldehyde Resin Systems**

In this section, the resin systems that have been used to produce panels with low-formaldehyde emissions are discussed. While interior-grade HWPW, PB, and MDF are all presently being made with UF resins, in future years, it may be necessary to consider an array of low HCHO resins given the manufacturing differences between HWPW, PB, and MDF. This is partly due to the stringency of present HWPW, PB, and MDF emission standards in the U.S., which have not kept pace with efforts in Europe and Japan, where the bulk of the research concerning low-formaldehyde resin technology is occurring.

While the commercial viability of soy resins for HWPW has been demonstrated in the U.S., staff expects that manufacturers will opt to use UF resins because of its low cost and versatility. To date, domestic efforts to lower HCHO emissions have been a consequence of work aimed at improving water resistance in composite wood products. As such, despite not being discussed in detail here, modified UF resins are likely to be the primary choice of manufacturers to achieve low HCHO emissions. Following optimization of plant-level operations and wood preparation, it is projected that the use of additives such as hexamine and melamine will be examined closely. Should these options prove to be too costly, the use of cost-effective non-UF resins might then be considered.

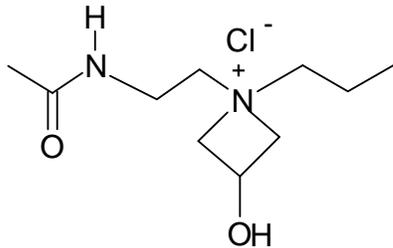
#### **1. Hardwood Plywood (HWPW) Resins**

##### **a. Soy-based Resins for Low-formaldehyde Hardwood Plywood**

Soy-based resins have been used since the early 20<sup>th</sup> Century (United Soybean Board, 2004), and research efforts have continuously focused on the development of resins with near-zero HCHO emissions, competitive pricing, and improved water resistance. In recent years, the use of soybeans (which are approximately 40% protein and approximately 34% carbohydrate), as a component in adhesives for plywood has grown, due in part to the abundance of key functional groups that all resins must have (Li et al., 2004). Proteins provide amine and amide functional groups, and carbohydrates provide hydroxyl groups

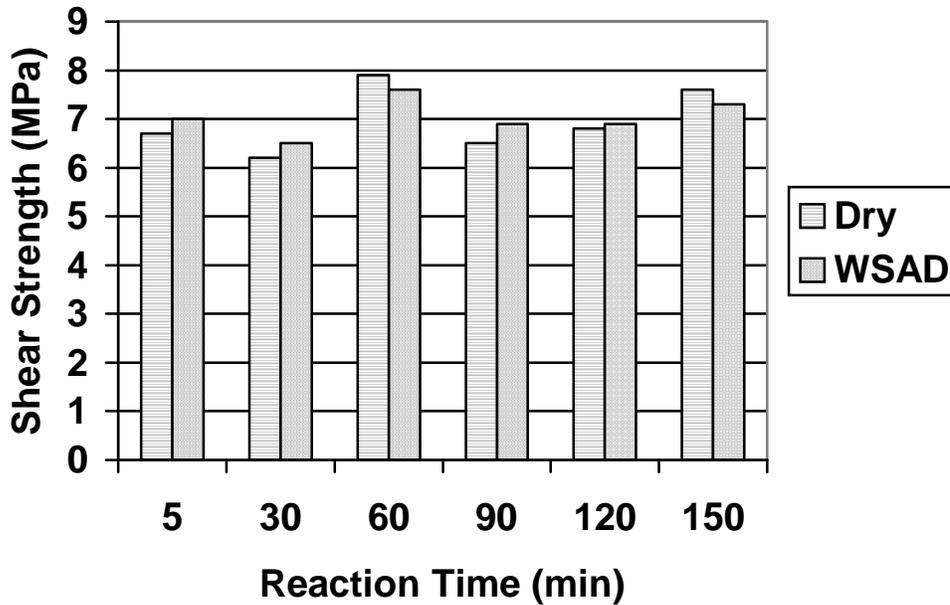
for high reactivity with a range of cross-linking agents (Heartland Resource Technologies, Not Dated).

Figure V-2. Cationic Polyamidoamine-epichlorohydrin (PAE)



Li et al. (2004) prepared a soy-based resin for plywood by combining soy protein isolate (SPI) with Kymene<sup>®</sup> 557H, a commercially available cationic polyamidoamine-epichlorohydrin (PAE) resin used in the paper industry (Figure V-2). Soy protein isolate is a soy product with a higher protein (86% vs. 40% by weight) and lower carbohydrate (14% vs. 34% by weight) content than soybeans. A plywood adhesive was prepared by mixing SPI and Kymene<sup>®</sup> at a dry weight ratio of 1.33:1. The maximum shear strength and water resistance were then determined on 1 x 10 cm plywood strips. Measurements of shear strength were made on dry plywood and plywood subject to a water-soaking-and-drying (WSAD) test, where the test materials were soaked in water at room temperature for 24-hours, and dried for 24-hours, prior to being measured (Figure V-3). No significant differences were observed in dry and WSAD shear strength at any reaction time. This indicated that plywood shear strength was not reduced after a WSAD test, and none of the plywood samples delaminated.

Figure V-3. Effect of Reaction Time on the Dry and Water-Soaking-and Drying (WSAD) Shear Strength of Plywood Made with a Soy Protein Isolate-Kymene<sup>®</sup> Resin<sup>1</sup>



<sup>(1)</sup> Source: Li et al. (2004). Shear strengths are the mean of 10 or more replicate measurements. Plywood was made with 1 x 10 cm strips of sugar maple veneer; press temperature = 120 °C, press time = 5 min; press pressure = 200 psi.

The SPI-Kymene<sup>®</sup> adhesive developed by Li et al. (2004) produced plywood with comparable shear strength properties to plywood made with a PF resin. However, SPI is very expensive, and at present-day prices, is not cost-competitive with PF. In comparison, soy flour is an inexpensive alternative that may have utility for plywood made for interior applications, which have lower interior strength and water-resistance requirements than exterior-grade plywood. As such, soy flour-Kymene<sup>®</sup> adhesives may be a cost-competitive no added HCHO replacement for UF resins in interior grade plywood. The use of a soy-based adhesive for HWPW was initiated by Columbia Forest Products, which markets its trademark Purebond<sup>™</sup> product line as HWPW made with a no added HCHO resin (Columbia Forest Products, 2005). In 2006, Columbia Forest Products began converting their HWPW-VC plants, which previously made HWPW-VC with a UF resin, to manufacturing Purebond<sup>™</sup>. Columbia Forest Products has stated that the use of Purebond<sup>™</sup> is cost-neutral to UF resin and meets the F☆☆☆☆ standard, and its utility as a resin for PB and MDF is currently being tested.

Heartland Resource Technologies has also developed a promising soy-based adhesive for HWPW called Soyad<sup>®</sup>. In this resin formulation, soy flour is combined with a PF resin (Heartland Resource Technologies, Not Dated). In their resin, soy flour is denatured in an alkaline environment to expose all

available amine and hydroxyl functional groups to make them accessible to crosslinking with the PF resin. When the soy flour is added to the PF resin for crosslinking, the bonds formed with HCHO are irreversible. In their experience, the manufacturing process is more user-friendly with soy-based resins, since no vacuum processing or high-pressure steps are involved (Westcott and Frihart, 2004). Heartland Resource Technologies has overcome many of the difficulties that were encountered in other efforts to develop a soy adhesive for HWPW (Table V-11).

Table V-11. Soy-based Adhesives: Problems and Solutions <sup>1</sup>	
Problems	Solutions
Biologically Unstable	Proper denaturing and copolymerizing with small amount of reactant improves product biological stability.
Low Solids	A new method for denaturing and copolymerizing with viable crosslinking agents was developed, allowing for soy resins with solids contents ranging from 30 to 45%.
Slow Press Times	Copolymerizing with reactive crosslinking agents allows for tailoring cure rates to meet a variety of applications.
Poor Water Resistance	Soy resins become water-resistant thermoset resins after copolymerizing with reactive crosslinking agents.
Very Short Shelf Life	Through innovative processing, the soy resin shelf life ranges from two weeks (similar to PF) to one year.
<sup>(1)</sup> <u>Source</u> : Wescott and Frihart (2004).	

Wescott and Frihart (2004) examined the properties of oriented strand board (OSB) made with a commercially available PF resin and soy-PF resins. Table V-12 lists the physical properties of the resins that were tested. The soy-PF resins were made using a soy:phenol ratio of either a 1:1 or 3.4:1 by weight. While the viscosity of the soy-PF resins were three- to four-times higher than the PF resin, the soy-PF resins could still be applied as a spray. This is because the soy-PF resins are thixotropic; their viscosity lowers when stress or high shear is applied, such as in the spraying process. As such, the viscosity of these soy-PF resins is lowered when it is sprayed, then it returns to its original viscosity after pressing and cooling. This property makes the resins easier to work into the manufacturing process and may have applications to PB and MDF. While the soy-PF resins had lower solids contents than the PF resin, values for percent extractables were similar for the 1:1 soy-PF resins and higher for the 3.4:1 soy-PF resin.

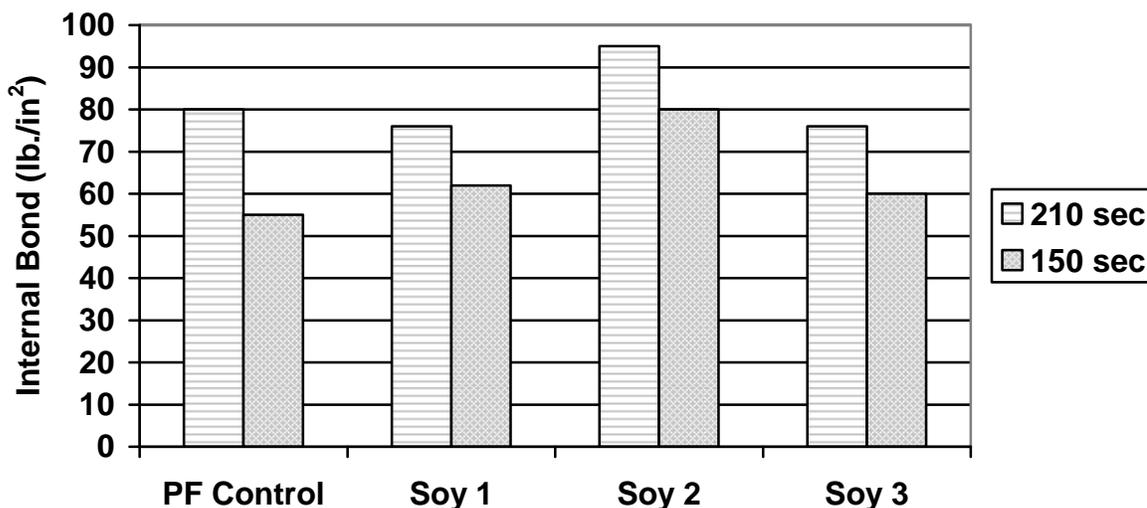
Table V-12. Physical Properties of Phenol-formaldehyde (PF) and Soy-PF Resins<sup>1</sup>

Property	----- Resin -----				
	PF	Soy-PF 1	Soy-PF 2	Soy-PF 3	Soy-PF 4
Soy:Phenol	0:1	1:1	1:1	1:1	3.4:1
Viscosity (mPa·s)	244	1,200	1,100	750	1,100
pH	11.2	10.2	11.3	11.3	10.3
% Solids	53.3	39.0	34.4	39.5	35
% Extractable	24	16	22	22	32

<sup>(1)</sup> Source: Westcott and Frihart (2004). "mPa·s" = millipascal-second.

In their OSB study, Westcott and Frihart (2004) used the soy-PF resins as a face resin, which they applied by air atomization. The <sup>7</sup>/<sub>16</sub>" OSB was formed on a 16" x 16" mat from yellow poplar strands with 5.6% moisture content to a target density of 42 lbs/ft<sup>3</sup> (674 kg/m<sup>3</sup>). The OSB made with a 1:1 soy:phenol ratio (i.e., Soy-PF 1-3), displayed dry internal bond strengths that were comparable to OSB made with the PF resin (Figure V-4). The OSB made with soy-PF 4 required a longer press time due to its higher soy content (data not shown). Further research is needed to optimize the crosslinking in soy-PF resins at soy:phenol ratios greater than 1:1.

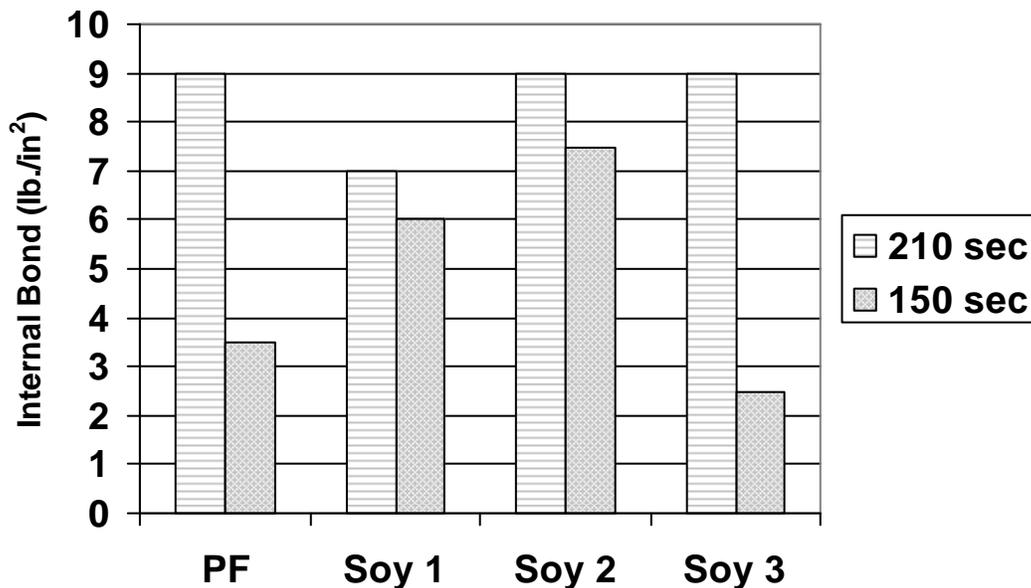
Figure V-4. Dry Internal Bond Strengths for Oriented Strand Board made with PF and Soy-PF Resins<sup>1</sup>



<sup>(1)</sup> Source: Westcott and Frihart (2004). Oriented Strand Board press temperature = 200 °C.

Wet internal bond strength was evaluated after applying the aggressive 2-hour boil test, where OSB is boiled for 2-hours and then oven-dried (Westcott and Frihart, 2004). As for the results of the dry internal bond test, OSB made with the 1:1 soy:phenol resins exhibited comparable results to OSB made with a PF resin (Figure V-5), indicating that soy resins can be used to produce OSB with excellent durability.

Figure V-5. Wet Internal Bond Strengths for Oriented Strand Board Made with Phenol-formaldehyde (PF) and Soy-PF Resins<sup>1</sup>



<sup>(1)</sup> Source: Westcott and Frihart (2004).

In conclusion, soy resins are an option for HWPW, and there are other researchers working to develop soy-based resins. For example, at Kansas State University, Dr. X. Susan Sun is developing a HCHO-free soy resin that is water resistant (K-State Media Relations & Marketing, 1998). The United Soybean Board is currently involved with soy binder research for large manufacturers of composite wood products (United Soybean Board, 2004).

b. Polyvinyl Acetate (PVA) Resins for Low-formaldehyde Hardwood Plywood

Polyvinyl acetate (PVA) is used to manufacture HWPW-VC for internal applications. It is a water-soluble adhesive that does not contain HCHO, and is one of the more flexible resins used to make plywood. Plywood made with PVA cures at lower temperatures than UF resins, thus allowing for reduced product cycle times (Steenbergen, 2000). The pot-life for PVA ranges from two to three

days after mixing compared to three or four hours for UF resins (Steenbergen, 2000). Under high moisture settings, PVA it does not bind as well as UF (Frihart, 2005).

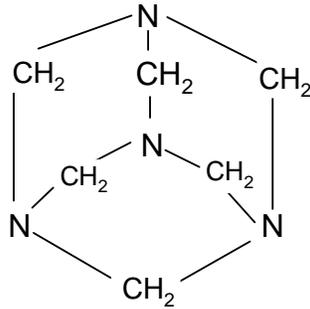
Franklin International (1999), among others, sells PVA that meets the requirements for the Hardwood Plywood & Veneer Association's HP-1 Type I and Type II plywood under several brand names (e.g., Multibond<sup>®</sup>, Titebond<sup>®</sup>, Advantage<sup>®</sup>). Polyvinyl acetate adhesives can be obtained as either one-part systems that come pre-mixed, or as a two-part system that utilizes a catalyst. Because PVA is a no added HCHO resin (i.e., does not use HCHO as part of the cross-linking structure), it could be used to make HWPW that would achieve low HCHO emission levels.

c. Tannin-based Resins for Low-formaldehyde Hardwood Plywood

The use of tannins, as a substitute for petroleum-based resins, has been studied for quite some time. Tannins are naturally phenolic and have been used commercially as a replacement for phenol or resorcinol in PF or phenol-resorcinol-formaldehyde (PRF) resins in Brazil, South Africa, and Australia (Santana et al., 1996). Different hardwood tannins, such as wattle and quebracho, have been produced and used commercially (Li and Maplesden, 1998). As a naturally occurring compound in trees, there is a real potential for tannins to be used in an aldehyde-free and no added HCHO adhesive for plywood, PB, and MDF. Three new tannin-based technologies, tannin-hexamine hardening, tannin autocondensation, and methylolated nitroparaffin hardening, are ready for use at the industrial-scale, and are presently being considered for use by a number of international manufacturers (Pizzi, 2006).

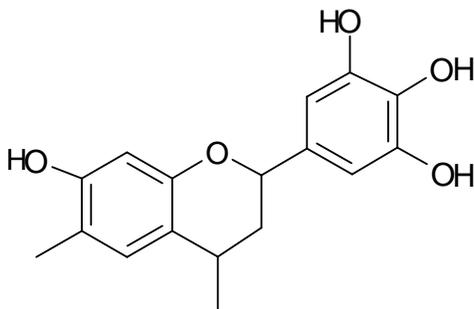
Hexamine (Figure V-6) is a nitrogen-containing compound that can be used as a tannin hardener (Kamoun et al., 2003). It readily reacts with the nucleophilic sites on tannins, resorcinol, and melamine. Under alkaline conditions, hexamine intermediates react with tannins before decomposition to HCHO. Tannin-hexamine resins are environmental-friendly; composite wood products made with these resins exhibit near-zero HCHO concentrations when measured using the JIS A5908 desiccator test (Pichelin et al., 2006). Pizzi et al. (1994) found that faster press times for products made with tannin-hexamine resins could be achieved by adding accelerators, such as zinc salts.

Figure V-6. Chemical Structure of Hexamine



Tannin autocondensation is a reaction that takes place between polyflavonoid tannins that consist of 5 to 11 monoflavonoid units. Monoflavonoid units consist of two phenolic rings joined by a heterocyclic ring (i.e., one or more atoms in the ring are atoms other than carbon) (Figure V-7). Under alkaline or acidic conditions, polyflavonoid tannins can autocondense in the absence of HCHO – the functional groups on a monoflavonoid in a tannin molecule can react with another monoflavonoid unit on a different tannin molecule. While the viscosity of the tannin increases, gelling does not occur (Pizzi, 2006). In order to control viscosity, increase pot-life, and avert gelation in tannins, methanol is usually added. Overall, tannin autocondensation reactions improve the dry strength of composite wood panels with little or no HCHO emissions.

Figure V-7. Chemical Structure of a Monoflavonoid Unit



Trosa and Pizzi (2001) compared the breaking loads and HCHO contents of plywood made with a quebracho tannin-based resin amended with a methylolated nitroparaffin (i.e., tris(hydroxymethyl)nitromethane or TN). The 10-mm plywood (5-ply okoume veneer) had an initial moisture content of 4%. Compared to plywood made with a MUF resin (M:U = 1), breaking loads in plywood made with tannin-TN resins were 22 to 67% lower (Table V-13).

However, when TN additions were 8% by weight or higher, measured breaking loads exceeded the minimum requirement of European Norm EN 314 Method 5.5.3. for exterior-grade plywood. In terms of HCHO content, the plywood made with the tannin-based resin with 10% TN had a DIN EN 120 value of 0.5 mg/100 g dry board, well below the European E1 standard of 8 mg/100 g dry board. These results show that the addition of TN, and potentially other methylolated nitroparaffins, to tannin-based resins, can both improve plywood strength and lower HCHO content.

Table V-13. Effect of Tris(hydroxymethyl)nitromethane (TN) Addition on the Breaking Loads and Formaldehyde Contents of Plywood Made with Quebracho Tannin Resin<sup>1</sup>

Resin or Standard	Breaking Load (MPa)	HCHO Emissions (mg/100 g panel)
MUF Control	2.7	6
Quebracho + 6% TN	0.9	NA
Quebracho + 8% TN	1.7	NA
Quebracho + 10% TN	2.1	0.5
EN 314 Standard	≥ 1.0	≤ 6.5

<sup>(1)</sup> Source: Trosa and Pizzi (2001). “MPa” = megapascals; “mg” = milligram(s); “g” = gram(s); “NA” = not available. Plywood press temperature = 120 °C; total press time = 6 minutes; press pressure = 8 kg/cm<sup>2</sup>; glue spread = 250 g/m<sup>2</sup>. EN 314 Standard refers to the European Standard for Class 3, Marine-grade plywood.

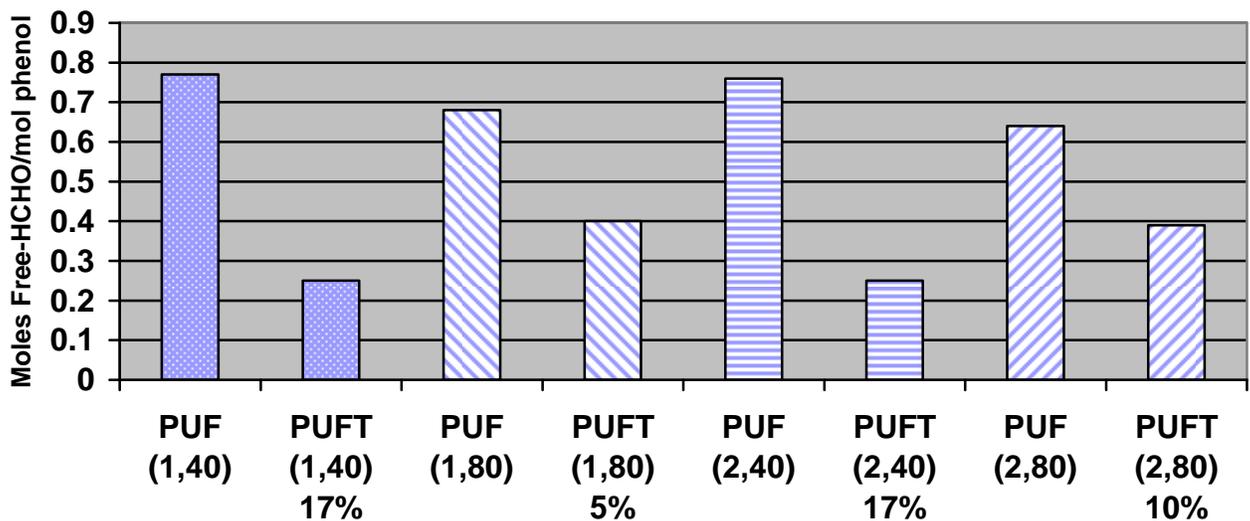
Tannin-based adhesives have also been used to manufacture various grades of HWPW in Brazil and China. To produce exterior-grade plywood, adhesives are fortified with other polymer systems, such as PF, RF, PRF, and MDI (Santana et al., 1997). Copolymerization with resol PF may also provide cost savings (approximately 20 to 40%) in that industrial applications allow for the use of 250 g/m<sup>2</sup> adhesive instead of 400 g/m<sup>2</sup>, as required for PF resin.

d. Phenol-urea-formaldehyde-Tannin (PUFT) Resins for Low-formaldehyde Hardwood Plywood

Tannins, which are phenolic in nature, can be used to replace phenol in PF resins. Vasquez et al. (2004) created a PUFT resin using PUF prepolymers and *Pinus pinaster* bark tannins, and compared the chemical characteristics of the resulting PUF and PUFT adhesives. The PUF and PUFT resins were prepared in two stages. The first stage involved reacting HCHO and phenol under acidic conditions for one or two hours, and the second involved reacting HCHO with urea under alkaline conditions for 40 or 80-minutes. The two-stage synthesis allowed the viscosity of the resin to be comparable to PUF resins used in commercial plywood facilities (1,300 to 3,000 mPa·s); however, the viscosity of

the PUFT resins increased over the 16 to 18 hour period between resin synthesis and chemical analysis. The PUFT resins displayed lower free-phenol contents than the PUF prepolymers and longer pot-lives (4 to 7 days) than other tannin-modified adhesive systems that were deemed unsuitable for use in plywood manufacturing. For the PUF resins, lower free-formaldehyde:phenol ratios were observed in resins with 80-minute stage two reaction times (Figure V-8). The PUFT resins, containing 5 to 17% tannin by weight, had 40 to 65% lower ratios of free-formaldehyde:phenol than comparable PUF resins. The PUFT resins with the highest tannin concentrations exhibited the lowest free-formaldehyde:phenol ratios. Spectral data indicated that the decrease in free-formaldehyde was due to methylation reactions between *Pinus pinaster* bark tannin and free-formaldehyde in the resin.

Figure V-8. Mole Ratios of Free Formaldehyde:Phenol in Phenol-urea-formaldehyde (PUF) and PUF-Tannin Resins<sup>1</sup>



<sup>(1)</sup> Source: Vasquez et al. (2004). The numbers in parentheses are the number of hours and minutes required for stage 1 and stage 2 resin synthesis, respectively. For PUFT resins, the % value is the tannin concentration on a weight basis.

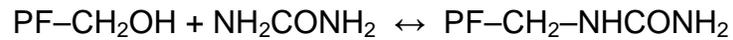
## 2. Particleboard (PB) Resins

### a. Phenol-urea-formaldehyde (PUF) Resins for Low-formaldehyde Particleboard

For the past 40-years, PB manufacturers have primarily used UF and PF resins. The use of low-cost UF resins has been dominant for interior applications, while PF resins are principally used to make exterior-grade products. The development of PUF resins was undertaken as a cost-control approach to

improving the durability and reducing HCHO emissions from interior-grade products (Tomita and Hse, 1998).

Zhao et al. (1999) examined the gel times for PF resins co-reacted with urea (up to 42%) under alkaline conditions, which promotes reactions between the hydroxyl groups on PF resins and amine groups on urea, as shown in the following:



Tests were conducted on samples of PB prepared in their laboratory made with a 9% PF resin solids content. The gel times of the PF resins with different F:P mole ratios and mole percentages of co-reacted urea are displayed in Table V-14. These results indicate that at the F:P mole ratios tested, increasing the amount of urea leads to faster gel times. The decrease in gel times with urea addition was thought to be due to an increase in molecular size of the polymer.

Table V-14. Gel Times (minutes) for Particleboard Made with Phenol-formaldehyde (PF) Resins Co-reacted with Urea <sup>1</sup>					
F:P Mole Ratio	----- Urea (Mole % of Phenol) -----				
	0	6	12	18	24
1.5	64.9	53.4	46.1	37.2	29.5
1.7	46	35.5	30.2	23.4	21.5
2.5	25.4	23.3	19.5	18.1	18.0

<sup>(1)</sup> Source: Zhao et al. (1999). Particleboard press temperature = 190 to 195 °C; maximum pressure = 28 kg/cm<sup>2</sup>.

These workers also examined the effects of urea addition on dry and wet internal bond strength of softwood PB bonded with a PF resin (F:P mole ratio = 1.7) (Table V-15). Their results showed that the dry and wet internal bond strengths are highest for softwood PB made a PUF resin with 12 to 24 mole-percent urea (i.e., dry strength > 1 MPa and wet strength ≥ 0.27 MPa). Spectral data confirmed that the greatest proportion of urea co-reaction with phenol occurs at 18 mole-percent urea, and that at urea mole-percentages greater than 12, there is virtually no free-formaldehyde in the PB.

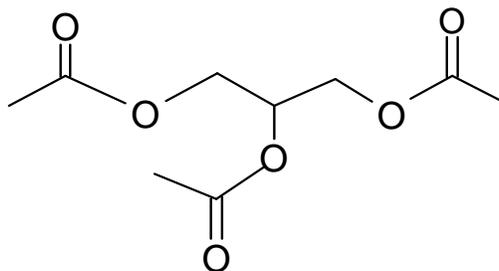
Table V-15. Effect of Urea Addition on Dry and Wet Internal Bond Strengths in Softwood Particleboard Bonded Phenol-formaldehyde (PF) Resin<sup>1</sup>

Resin	Dry Internal Bond (MPa)	Wet Internal Bond (MPa)
PF Control	0.88	0.20
+ 6% urea	0.91	0.26
+ 12% urea	1.07	0.30
+ 18% urea	1.09	0.31
+ 24% urea	1.12	0.28
+ 30% urea	0.98	0.25
+ 36% urea	0.94	0.24
+ 42% urea	0.96	0.25

<sup>(1)</sup> Source: Zhao et al. (1999). Wet internal bond strength was measured after the particleboard was boiled for two-hours and dried. The F:P mole ratio of the PF control resin = 1.7.

The process throughput of PB made with PF resins is typically slower than that for PB made with UF resins, where the fastest press times for PB made with a commercial PF resin is reported to be 12 to 13 s/mm at a press temperature of 190 °C (Zhao et al., 1999). To achieve faster press times, manufacturers can either use higher press temperatures or add carbonate accelerators. The effectiveness of glycerol triacetate or triacetin (Figure V-9) has been tested in PUF resins as an means to accelerate PUF resin crosslinking and increase the board strength.

Figure V-9. Chemical Structure of Triacetin



Zhao et al. (1999) found that the press time for hardwood PB bonded with a PUF resin (i.e., F:P mole ratio = 1.7, urea = 24 mole-percent) could be reduced from 21.4 to 8.5 s/mm without decreasing dry or wet internal bond strength, by addition of triacetin (Table V-16). The press times they achieved were comparable to those of a catalyzed UF resin. The hardwood PB made using an 8.5 s/mm press time, exhibited dry and wet internal bond strengths that would

readily comply with the European Norm (EN 300, 1996) or German DIN standards (DIN 68763) of 0.35 MPa or greater and 0.15 MPa or greater, respectively. At a 7.1 s/mm press time, dry and wet internal bonds were markedly lower than at 21.4 s/mm, but the resulting dry and wet internal bond strengths would still comply with European and German standards. Similar reductions in press times may also be achieved by raising press temperatures to 200 to 220 °C without reducing internal bond strength to levels below the standard(s). Board densities ranged only slightly, from 729 to 753 kg/m<sup>3</sup>, over the range of press times tested.

Press Time (s)	Press Time (s/mm)	Dry Internal Bond (MPa)	Board Density (kg/m <sup>3</sup> )	Wet Internal Bond (MPa)
300	21.4	0.85	753	0.23
240	17.1	0.93	758	0.28
180	12.9	0.95	729	0.29
150	10.7	0.95	732	0.30
120	8.5	0.81	751	0.22
100	7.1	0.52	735	0.15
90	6.4	0.49	741	0.11

<sup>(1)</sup> Source: Zhao et al. (1999). Wet internal bond strength was measured after the PB was boiled for two-hours and dried. Particleboard was bonded with PUF resin with a F:P mole ratio = 1.7; 24 mole-percent urea, and 10% triacetin by weight. "s" = seconds; "s/mm" = seconds per millimeter; "MPa" = megapascals; "kg/m<sup>3</sup>" = kilograms per cubic meter.

b. Tannin-based Resins for Low-formaldehyde Particleboard

The effort to decrease or eliminate surface HCHO emissions from PB using tannin-based resins is a work-in-progress. There are tannin technologies that are viable for commercial use in Australia, New Zealand, Chile, Brazil, Argentina, and South Africa (Frihart, 2005). Interest in using tannin-based resins is growing in Japan and Europe. In this regard, tannin autocondensation, an environmental-friendly technology previously described subsection IV.A.3. for HWPW, can also be used for manufacturing PB.

Pizzi et al. (1995) measured the HCHO content of PB made with resin produced by pecan nut (*Carya illinoensis*) tannin autocondensation. Over a range of press times from 10 to 37.5 s/mm, HCHO contents in PB ranged from 0.01 to 0.03 mg/100 g dry board (by the DIN EN 120 test). These data demonstrate the potential utility of tannin-based resins for producing PB with low HCHO contents. To determine if the structural properties of PB made with tannin-based resins

were adversely affected, these workers measured the internal bond strength of PB made with four commercial flavonoid tannin-based resins (i.e., pecan nut (*C. illinoensis*), pine bark (*Pinus radiata*), mimosa bark (*Acacia mollissima*), and quebracho wood (*Schinopsis balansae*)). The 12-mm PB used in the study was made by pressing wood particles with 3% moisture content for 7.5 minutes at 190 °C. Board densities ranged from 680 to 700 kg/m<sup>3</sup>. While the internal bond strengths for PB made with pine and pecan resins were as high as 0.8 MPa, the values for PB made with mimosa or quebracho resins were 0.3 MPa or less. However, when pecan nut tannin (40% by weight) was added to the mimosa or quebracho resins, internal bond strengths increased by four- to five-fold. The increase in internal bond strength was thought to be due the presence of more reactive tannin “A-rings” in pecan nut and pine bark than in mimosa bark or quebracho wood. Press times could also be improved by the addition of finely powdered silica.

In comparison, Kim et al. (2003) measured the mechanical and physical properties of PB made with two tannin-hexamine resins (subsection IV.A.3.). Two other hardeners besides hexamine were tested, but only the results for hexamine are discussed here. Commercial tannin extracts from wattle (or mimosa (*Acacia mearnsii*)), and radiata pine (*Pinus radiata*) were provided by Bondtite (New South Wales, Australia) and DITECO (Punta Arenas, Chile), respectively. Hexamine (i.e., 6.5, 8, and 10% by weight of dry tannin extract) was added to each tannin extract. The PB was pressed at temperatures ranging from 160 to 190 °C for 5-minutes at a pressure of 30 kg/cm<sup>2</sup>, and released in (two) one-minute steps. The 8-mm PB was preconditioned at 25 °C and 65% relative humidity for two weeks before testing. The HCHO contents of the PB were measured by the DIN EN 120 test. Particleboard produced with either tannin-hexamine resin had very low HCHO content; the values for wattle and pine were 0.85 and 1.75 mg HCHO/100 g dry board, respectively. By extrapolation, PB with these DIN EN 120 values would have ASTM E1333 values less than 0.03 ppm, which may meet the Japanese F☆☆☆☆ standard. In comparison, the proposed Phase 2 standard for PB is 0.08 ppm.

Kim et al. (2003) also examined changes in bending (modulus of rupture) and internal bond strength in PB made with the wattle and pine tannin-hexamine resins. The two tannins differ with respect to their A-ring reactivity, which affect their curing properties. The resin made with wattle tannin is more of a thermosetting resin, in which functional group cross-linking increases with press temperature, whereas the resin made with pine tannin is fast-reacting, and cures at lower press temperatures. As projected, PB made with the wattle tannin-hexamine resin exhibited a stronger modulus of rupture and internal bond strength as press temperature was raised from 160 to 190 °C, while the responses of PB made with the pine tannin-hexamine resin decreased with increasing press temperature. Overall, PB made with either tannin-hexamine resin exhibited strength properties that exceeded the minimum requirements for Grade M-3 industrial or shelving PB (Table V-17; ANSI, 1999).

Table V-17. Minimum American National Standards Institute (ANSI) Strength Requirements for Medium (M) Industrial and Shelving Grade Particleboard <sup>1</sup>			
Grade	----- Minimum Strength Requirement (MPa) -----		
	Modulus of Rupture	Modulus of Elasticity	Internal Bond
M1	11.0	1,725	0.40
MS	12.5	1,900	0.40
M2	14.5	2,250	0.45
M3	16.5	2,750	0.55

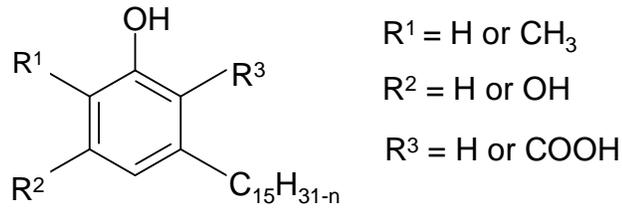
<sup>(1)</sup> Source: ANSI (1999). Listed values are those specified for the ANSI A208.1 standard.

In other studies to identify additives that would both lower HCHO contents and strengthen the physical properties of PB, Trosa and Pizzi (2001) added a methylolated nitroparaffin (i.e., tris(hydroxymethyl)nitromethane or TN) to a tannin-based resin and produced PB with satisfactory structural properties for dry internal bond and 2-hour boil test strengths, and low HCHO emissions (DIN EN 120 = 0.3 to 0.6 mg/100 g dry board). Ballerini et al. (2005) used a tannin-glyoxal adhesive to produce PB with very low HCHO contents (i.e., DIN EN 120 = 0.6 mg/100 g dry board). Glyoxal is a simple di-aldehyde that has a low toxicity and can be substituted for HCHO. Either of the above additives, TN or glyoxal, could be used to produce PB that would comply with the proposed Phase 2 standard (0.08 ppm).

c. Cashew Nut Shell Liquid (CNSL) Resins for Low-formaldehyde Particleboard

Cashew nut shell liquid (CNSL) is a naturally occurring product that chemically has phenolic nuclei with unsaturated fatty acid chains (Figure V-10), and has potential utility as an additive for improving water-resistance in PB, and possibly other composite wood products (Pizzi, 2006). Presently, the major source continents of CNSL are South America and Asia; however, there are a number of cashew plantations in Mozambique (Kanji et al., 2004). At BC (formerly the BioComposites Center, Bangor, Wales), reactive aldehyde monomers were prepared by ozonolysis of CNSL. As an additive to PB resin, the aldehyde monomers react with the aromatic groups of cardanol (i.e., anacardic acid) and produce a phenol/aldehyde crosslinking network. As these monomers are very reactive, self-condensation occurs and no crosslinking agent needs to be added to the mixture.

Figure V-10. Chemical Composition of Cashew Nut Shell Liquid



- Anacardic acid ( $R^1 = \text{H}, R^2 = \text{H}, R^3 = \text{COOH}$ )
- Cardanol ( $R^1 = \text{H}, R^2 = \text{H}, R^3 = \text{H}$ )
- Cardol ( $R^1 = \text{H}, R^2 = \text{OH}, R^3 = \text{H}$ )
- Methyl cardol ( $R^1 = \text{CH}_3, R^2 = \text{OH}, R^3 = \text{H}$ )

The CNSL-based resin technology is in early stages of development, thus, it is difficult to evaluate its economical feasibility. However, strength tests of PB made in a laboratory with CNSL-based resins are promising (Table V-18). Compared to PB made with PF resin, PB made with a CNSL-based resin had higher lap-shear bond and dry internal bond strengths. These findings provide support for the use of CNSL-based resins in PB manufacturing (Pizzi, 2006), but additional information on press time and board density is needed to fully assess its cost-effectiveness in industrial applications.

Table V-18. Strength Responses in Particleboard Made with Phenol-formaldehyde (PF) and Cashew Shell Nut Liquid (CNSL) Resins <sup>1</sup>			
Resin	----- Strength (MPa) -----		
	Lap-shear Bond	Dry Internal Bond	Wet Internal Bond
PF Control	5.55	0.69	NR
CNSL	6.77	1.05	0.58

<sup>(1)</sup> Source: Pizzi (2000). “MPa” = megapascals; “NR” = not reported. Wet internal bond strength was measured after the particleboard was boiled for two-hours and dried.

d. Soy-based Resins

Work continues to develop soy resins that can be used to produce PB (Heartland Resource Technologies, Not Dated). Recently, Columbia Forest Products announced the availability of a Purebond™ PB, which is being used as the platform for its composite core plywood products.

### 3. Medium Density Fiberboard (MDF) Resins

#### a. Tannin-based Resins for Low-formaldehyde Medium Density Fiberboard

Three tannin-based technologies (i.e., hexamine addition, autocondensation, and methylolated nitroparaffin addition; see subsection IV.A.3.) that have potential utility in the manufacture of HWPW and PB, have also been found to be applicable to MDF.

Trosa and Pizzi (2001) found that exterior/marine-grade HWPW, PB, and MDF, with very low HCHO emissions, could be made with a tannin-based resin by adding an inexpensive methylolated nitroparaffin (i.e., tris(hydroxymethyl)-nitromethane or TN). In their study, the addition of TN prolonged the pot-life of the tannin-based resin, and HCHO emissions only occurred when the wood was heated – at lower temperatures, the resin appeared to depress HCHO emissions originating from wood used to make the boards. Comparison of HCHO content and measures of strength and swell were conducted on 3-mm MDF made from pine wood fibers in plant trials with either UF or quebracho tannin-based resin (i.e., total tannin solids, TN, and wax emulsion contents were 14%, 16%, and 2%, respectively). Relative to the MDF made with UF resin, the MDF made with the tannin-based resin had a higher bending strength and lower free-HCHO content (Table V-19), but no differences were observed in cold water swell, board density, or dry internal bond strength. The free-HCHO content of the MDF was low enough to meet the requirement for E0 boards, which is lower than the proposed Phase 2 standard for MDF of 0.08 ppm. Similar results were also obtained for HWPW and PB made with the tannin-based resin. As an additive to tannin-based resins, TN could be added with other HCHO-based resin hardeners (e.g., methylolureas, paraformaldehyde) over a broad range without loss of effectiveness.

Table V-19. Density, Swell, Strength, and Formaldehyde Content in Medium Density Fiberboard Made with Urea-formaldehyde (UF) and Quebracho Tannin-based Resins<sup>1</sup>

Parameter	----- Resin -----	
	Quebracho Tannin	UF Control
Density (kg/m <sup>3</sup> )	870	870
Cold Water Swell (20 °C for 24-hours)	14%	14%
Bending Strength (MPa)	38	30
Dry Internal Bond Strength (MPa)	1.8	1.8
HCHO Content (mg/100 g dry board)	0.0	0.9

<sup>(1)</sup> Source: Trosa and Pizzi (2001). “kg/m<sup>3</sup>” = kilograms per cubic meter; “°C” = degrees Celsius; “MPa” = megapascals; “mg” = milligrams. Medium density fiberboard (3-mm thickness) press temperature = 180 °C, press time = 22 s/mm; maximum press pressure = 170 Bar. The quebracho tannin-based resin contained 16% tris(hydroxymethyl)nitromethane and 2% wax emulsion by weight.

b. Phenol-urea-formaldehyde-Tannin (PUFT) Resins for Low-formaldehyde Medium Density Fiberboard

As the cost of petrochemical-based resin components rise (e.g., phenol), the search for lower cost alternatives is of increasing concern to resin manufacturers. For HWPW and MDF, phenol-urea-formaldehyde-tannin (PUFT) resins have been tested with promising results, in which increasing amounts of tannins can be added in place of phenol.

Lopez-Suevos and Riedl (2003) measured the dry and wet internal bond strengths of MDF made with three PUFT resins. The PUFT resins were made by adding 35% *Pinus pinaster* bark tannin solution to a PUF resin (40% solids content by weight). Three PUFT resins were prepared: PUFT-10, PUFT-12, and PUFT-15 (the numbers indicate the % tannin content by weight). The MDF was made with 90% black spruce and 10% Douglas-fir fibers with an initial moisture content of 3%. Relative to dry or wet internal bond strength, only MDF made with PUFT-10 had values comparable to MDF made with a PF resin (Table V-20). The MDF made with PUFT-15 or PUFT-12, even when pressed for 8.83 minutes, exhibited markedly lower dry and wet internal bond strengths, that may be due to a higher degree of resin condensation (i.e., when larger resin molecules form, which do not bond as tightly to wood fibers as smaller molecules). While all of the MDF tested exhibited dry internal bond strengths above the European standard for interior-grade MDF (0.6 MPa; EN 319), only the MDF made with the PF or PUFT-10 resins would comply with the dry and wet internal bond strength standards for exterior-grade MDF (0.8 and 0.15 MPa, respectively). The PUFT-10 resin, which has a 44% phenol replacement by tannins, could conceivably be a cost-competitive resin for MDF, which may also have a low HCHO content.

Table V-20. Dry and Wet Internal Bond Strengths of Medium Density Fiberboard Made with Phenol-formaldehyde (PF) and Phenol-urea-formaldehyde-tannin (PUFT) Resins<sup>1</sup>

Resin (Press Time)	Density (kg/m <sup>3</sup> )	----- Strength (MPa) -----	
		Dry Internal Bond	Wet Internal Bond
PF Control (5.33 min)	727	1.18	0.58
PUFT-15 (5.33 min)	771	0.74	0.09
PUFT-15 (6.83 min)	706	0.62	0.07
PUFT-15 (8.83 min)	710	0.68	0.08
PUFT-12 (5.33 min)	734	0.72	0.13
PUFT-10 (5.33 min)	732	1.10	0.20
PUFT-10 (8.83 min)	728	1.42	0.44

<sup>(1)</sup> Source: Lopez-Suevos and Riedl (2003). "MPa" = megapascals; "kg/m<sup>3</sup>" = kilograms per cubic meter. Medium density fiberboard press temperature = 215 °C.

## E. Technical Basis for the Proposed Emission Standards

### 1. Proposed Emission Standards for Hardwood Plywood

Appendix A contains the regulation order for the proposed ATCM. For HWPW, made with a veneer core (HWPW-VC) or with a composite core (HWPW-CC), the numerical values of the proposed Phase 1 and 2 HCHO emission standards are based on analyses of manufacturer responses to the CARB 2003 Survey, data supplied by the Hardwood Plywood & Veneer Association (HPVA), reports or articles in the open literature, commercial brochures, and other published materials or websites, and stakeholder meetings, concerning resin technologies that are either commercially available or laboratory tested to display low or near-zero HCHO emissions. The proposed standards and effective dates for HWPW-VC and HWPW-CC are shown in Table V-21.

Table V-21. Proposed Phase 1 (P1) and Phase 2 (P2) Formaldehyde (HCHO) Emission Standards for Hardwood Plywood <sup>1</sup>		
Effective Date	HCHO Emission Standard	
	HWPW-VC	HWPW-CC
January 1, 2009	P1: 0.08 ppm	-----
July 1, 2009	-----	P1: 0.08 ppm
January 1, 2011	P2: 0.05 ppm	-----
July 1, 2012	-----	P2: 0.05 ppm
<sup>(1)</sup> "ppm" = parts per million; "HWPW-VC" = hardwood plywood with a veneer core; "HWPW-CC" = hardwood plywood with a composite core. Compliance with the HCHO Emission Standards is demonstrated by producing HWPW-VC and HWPW-CC with an ASTM E1333 test value less than or equal to the listed P1 or P2 HCHO concentration in ppm.		

From the CARB 2003 Survey, approximately 20% of the HWPW-VC or HWPW-CC produced for sale in 2002 achieved, on average, an ASTM E1333 test value that would meet the proposed Phase 1 standard of 0.08 ppm. However, as the survey respondents did not distinguish if the information they provided was for decorative wall panels or industrial panels, industry representatives are concerned that the above estimate may not be accurate. Note that the survey was conducted before Columbia Forest Products switched to using Purebond™ and now about 40% of the HWPW in the U.S. meets the Phase 2 standard. In the ASTM E1333 test, decorative wall panels are tested at a higher loading rate (0.29 ft<sup>2</sup>/ft<sup>3</sup>) than industrial panels (0.13 ft<sup>2</sup>/ft<sup>3</sup>). Thus, unless it can be determined which type of HWPW-VC or HWPW-CC was measured, an accurate analysis of industrial panel emissions cannot be made with certainty. From the survey, all of the HWPW-VC or HWPW-CC that achieved an ASTM E1333 value of 0.08 ppm

was made with an ammonia-UF (AUF) resin with added catalysts or hardeners to reduce surface HCHO emissions. These AUF resins were reported to have high F:U mole F:U ratios ranging from 1.7 to 1.98. Absent clear information regarding the need to develop a new standard for decorative wall panels, no change is proposed with respect to the loading rates presently used for ASTM E1333 testing.

To produce HWPW-VC or HWPW-CC that would meet the proposed Phase 1 emission standard (a 0.08 ppm cap), manufacturers that choose to use UF resins could use resins with lower F:U mole ratios (e.g., 1.05 to 1.20; Baumann, 1997) to lower their emissions below their present ASTM E1333 levels. Further reductions could be achieved through the use of additives such as ammonium chloride or hexamine, which act as hardeners or catalysts, in amounts ranging from 1 to 4% by weight. The combined use of a lower F:U mole ratio resin and addition of hardeners should enable manufacturers to produce HWPW-VC or HWPW-CC that complies with the proposed Phase 1 standard. However, as none of the reported HWPW-VC or HWPW-CC was able to comply, on average, with the proposed Phase 2 standard (a 0.05 ppm cap), manufacturers may need to utilize a reformulated resin system or another resin system than UF. While laboratory studies indicate that reductions in HCHO emissions can be achieved by the addition of melamine and/or MDI, it will be up to manufacturers to determine how best to manufacture HWPW-VC or HWPW-CC that meets the proposed Phase 2 standard.

From analysis of the data provided by the Hardwood Plywood & Veneer Association, the issue of whether to establish separate HCHO emission standards for HWPW-VC and HWPW-CC was clarified. Previously, stakeholders requested that CARB staff consider setting separate standards because the core material in HWPW-CC was typically either PB or MDF, which has higher allowable emissions than HWPW. In calculating mean ASTM E1333 values for HWPW-VC and HWPW-CC from the data provided by the HPVA, the means for HWPW-VC and HWPW-CC were 0.12 ppm (n = 14) and 0.08 ppm (n = 5), respectively (Tables V-4 and V-5). Moreover, the range in ASTM E1333 values for HWPW-VC was 0.08 to 0.19 ppm vs. 0.05 to 0.10 ppm for HWPW-CC. As this was counterintuitive to the justification offered by stakeholders from the HWPW industry for separate standards, the numerical values of the proposed Phase 1 and Phase 2 standards, which apply to HWPW-VC and HWPW-CC, are the same. Additional time is provided for HWPW-CC to allow for the availability and use of lower emitting core materials.

In evaluating BACT for HWPW, an internet search uncovered products from three U.S. sources, either HWPW panels or resin used to manufacture HWPW, that could be used immediately to produce HWPW that complies with the proposed Phase 2 standard (Table V-22).

Table V-22. Low-formaldehyde Hardwood Plywood (HWPW) or HWPW-Resins<sup>1</sup>

Product	Company	HCHO Emissions	Resin System
Purebond™	Columbia Forest Products	Near-zero	Soy-based
Multibond®	Franklin Adhesives	Near-zero	PVA
Purekor®	Collins Pine Company	Near-zero	MDI

(1) "Near-zero" emissions indicates measured ASTM E1333 test values = 0.03 ppm or less.

From the literature and stakeholder discussions, there are resins that have the potential to be used to manufacture HWPW to meet the proposed Phase 1 and Phase 2 standards, such as soy-based, PVA, MUF, PUF, PUF-tannin, and several MDI hybrid systems, and the resin preparation and application methods are well documented. As such, staff proposes that the numerical value of the Phase 1 standard for HWPW, regardless of core composition, be a cap of 0.08 ppm measured by the ASTM E1333 test, with effective dates of January 1, 2009 for HWPW-VC and July 1, 2009 for HWPW-CC. For Phase 2, the proposed standard would be a cap of 0.05 ppm measured by the ASTM E1333 test, regardless of core composition, with effective dates of January 1, 2011 for HWPW-VC and July 1, 2012 for HWPW-CC.

For Phase 2, careful consideration was given to the absolute value of the proposed standard, requirements of the present ASTM E1333 test and the potential for higher emitting products in core materials (e.g., PB or MDF) to raise measured HCHO concentrations in the ASTM E1333 test.

## 2. Proposed Emission Standards for Particleboard

As for HWPW, the numerical values for the proposed Phase 1 and Phase 2 HCHO emission standards are also based on analyses of the CARB 2003 Survey. In addition, a review of the literature and expert opinions provided by industry and stakeholders on the range of resin and wood preparation technologies that could be used to manufacture PB with low to near-zero surface HCHO emissions were considered. The proposed standards and effective dates for PB are shown in Table V-23.

Table V-23. Proposed Phase 1 (P1) and 2 (P2) Emission Standards for Particleboard <sup>1</sup>	
Effective Date	HCHO Emission Standard
January 1, 2009	P1: 0.18 ppm
January 1, 2011	P2: 0.09 ppm
(1) "ppm" = parts per million. Compliance with the HCHO Emission Standards is demonstrated by producing particleboard with an ASTM E1333 test value less than or equal to the listed P1 or P2 HCHO concentration in ppm.	

Analysis of the CARB 2003 Survey data for PB found that approximately 55% of the PB produced in 2002, on average, would comply with the proposed Phase 1 standard of 0.18 ppm. The predominant resins used were UF or methanol-UF resins, and PB manufacturers that reported the lowest average ASTM E1333 values (i.e., less than 0.18 ppm) achieved those levels by adding low mole ratio urea solutions (which act as a HCHO scavenger) and/or a variety of catalysts, such as ammonium sulfate, sodium chloride, and sodium sulfate.

Table V-24. Low-formaldehyde Particleboard (PB) and PB-Resin Systems <sup>1</sup>			
Product	Company	ASTM E1333 Value	Resin Chemistry
Low-formaldehyde Particleboard			
Purekor <sup>®</sup>	Collins Pine	Near-zero	MDI
Skyblend <sup>®</sup>	Roseburg	≤ 0.01 ppm	PF
Low-formaldehyde Particleboard Resin Systems			
Ecobind <sup>®</sup>	Hexion	≤ 0.03 ppm	MUF + Co-reactants PF Soy/PVA blend
Kenocatch <sup>®</sup>	Akzo Nobel	≤ 0.03 ppm	MUF + catcher
Rubinate <sup>®</sup>	Huntsman	Near-zero	Polyurethane
(1) "MDI" = methylene diisocyanate; "PF" = phenol-formaldehyde; "MUF" = melamine-urea-formaldehyde; "PVA" = polyvinyl acetate; "ppm" = parts per million. "Near-zero" refers to an extrapolated ASTM E1333 value less than 0.03 ppm.			

No manufacturer reported producing PB with an average ASTM E1333 value that would meet the proposed Phase 2 standard of 0.09 ppm, although after an internet search, a short-list of commercially available low-formaldehyde PB or

resins used to manufacture PB was developed (Table V-24). Both PB products are made for niche markets (e.g., Green Building Programs) that specify the use of low- or no added HCHO materials. These resin systems, if used in combination with additives or low-formaldehyde resins developed outside the U.S., may potentially be used meet the proposed Phase 2 standard.

3. Proposed Emission Standards for Medium Density Fiberboard

As for HWPW and PB, analysis of the data from the CARB 2003 Survey, information in the open literature and expert opinions on low- and no added HCHO resin technologies, were the main data considered with respect to selecting the numerical values of the proposed Phase 1 and 2 emission standards for MDF. The proposed standards and their effective dates are shown in Table V-25 for MDF.

Table V-25. Proposed Phase 1 (P1) and Phase 2 (P2) Standards for Medium Density Fiberboard <sup>1</sup>	
Effective Date	HCHO Emission Standard
January 1, 2009	P1: 0.21 ppm
January 1, 2011	P2: 0.11 ppm
<p>(1) "ppm" = parts per million. Compliance with the HCHO Emission Standards is demonstrated by producing MDF with an ASTM E1333-96 test value less than or equal to the listed P1 or P2 HCHO concentration in ppm.</p> <p>(2) Thin MDF Phase 1 standard is 0.21 ppm (January 1, 2009), and Phase 2 standard is 0.13 ppm (January 1, 2012)</p>	

From the CARB 2003 Survey, approximately 25% of MDF reported for sale in 2002, on average, would comply with the proposed Phase 1 standard (0.21 ppm). All of the manufacturers that reported producing MDF at an average ASTM E1333-96 of 0.21 ppm or less made their products with a UF resin. In our view, MDF manufacturers would be able to consistently meet the Phase 1 standard by using low mole ratio urea solutions (which act as a scavenger), and/or a variety of catalysts, such as melamine, ammonium sulfate, sodium chloride, and sodium sulfate, or proprietary scavengers. Making MDF with a MDI resin would also be a viable approach for meeting the Phase 1 and 2 standards, but at present, MDI use is typically limited to the production of products for niche applications (e.g., hospitals). These resin systems are just a few of the ways that MDF manufacturers could meet the proposed Phase 2 standard (0.11 ppm cap) (Table V-26).

Table V-26. Available Low-formaldehyde Medium Density Fiberboard (MDF) or MDF-resins<sup>1</sup>

Product	Company	HCHO Emissions	Resin Chemistry
Low-formaldehyde Medium Density Fiberboard			
<ul style="list-style-type: none"> <li>• Arreis<sup>®</sup></li> <li>• Medite II<sup>®</sup></li> <li>• Medex<sup>®</sup></li> </ul>	Sierra Pine	≤ 0.05 ppm	MDI
Purekor <sup>®</sup>	Collins Pine	Near-zero	MDI
Low-formaldehyde MDF-resins			
Ecobind <sup>®</sup>	Hexion	≤ 0.03	<ul style="list-style-type: none"> <li>• MUF + Co-reactants</li> <li>• PF</li> <li>• Soy/PVA Blend</li> </ul>
Kenocatch <sup>®</sup>	Akzo Nobel	≤ 0.03	MUF + Catcher
Rubinate <sup>®</sup>	Huntsman	Near-zero	Polyurethane

<sup>(1)</sup> “MDI” = methylene diisocyanate; “PF” = phenol-formaldehyde; “MUF” = melamine-urea-formaldehyde; “PVA” = polyvinyl acetate; “ppm” = parts per million. “Near-zero” refers to an extrapolated ASTM E1333 value less than 0.03 ppm.

#### 4. Thin Medium Density Fiberboard (MDF) (Thickness ≤ 8-mm)

“Thin MDF” is defined as MDF with thicknesses of 8 mm ( $\approx 5/16$  inch) or less. While the amount of thin MDF production is not known with certainty, to our knowledge, it represents a small percentage of total MDF production in the U.S. Thin MDF, at thicknesses starting at 1.8 mm, is being manufactured and used as a substitute for hardboard and thin plywood due to its being smooth on both surfaces and free from the grain features of plywood substrates (European Panel Federation, Not Dated). Fabricators use these materials in furniture (e.g., drawer bottoms, cabinet backs, and center panels in framed doors) and as wall and ceiling panels, skins in flush doors, partitioning, lightweight doors, and exhibition paneling for inside-building applications (e.g., offices, reception areas, classrooms, and exhibition displays).

From CARB’s 2003 Survey, only two MDF manufacturers listed thin MDF as a product that they offer for sale. One manufacturer reported ASTM E1333 values ranging from 0.17 to 2.5 ppm for MDF ranging in thickness from 8 mm to  $5/8$ ”; however, none of the reported ASTM E1333 values could be specifically assigned to thin MDF. The second manufacturer reported ASTM E1333 values

ranging from 0.20 to 0.37 ppm for their thin MDF made with a UF resin (exact thickness was not provided). A web-search for manufacturers of thin MDF found Fibrex<sup>®</sup> manufactured by Flakeboard Company Limited (Flakeboard, 2005), which is described as a high density, thin MDF. As the average ASTM E1333 values for this product were reported to be less than 0.2 ppm, it would presently comply with the proposed Phase 1 standard for MDF (i.e., 0.21 ppm). From the Composite Panel Association (CPA) website (CPA, 2006), one other manufacturer indicated the availability of thin MDF, that presumably complies with the HUD standard (0.3 ppm).

Recently, a U.S. manufacturer reported that the thin MDF they produce exhibited ASTM E1333 values of 0.7 ppm or higher, consistent with one of the manufacturers that responded to the CARB 2003 Survey. As such, they contend that it is unlikely that thin MDF can be made to comply with the proposed Phase 1 (0.21 ppm) and Phase 2 standards (0.11 ppm), and consideration be given to setting a separate standard for MDF of thicknesses less than 8 mm. While the specific application for the 0.7 ppm product is not known, given the existence of Flakeboard's Fibrex<sup>®</sup> and the prospects for a full range of no added urea-formaldehyde MDF products from CalAg (Sustainable Design Resources, 2003), there is a reasonable basis for projecting that thin MDF could be manufactured to comply with the proposed Phase 1 standard of 0.21 ppm for thin MDF in January 2009 and the proposed Phase 2 standard of 0.13 ppm in January 2012.

#### 5. ASTM E1333 Background Concentration

The large chamber test method (ASTM E1333) is the industry recognized test method for measuring surface emissions of HCHO from composite wood products in the U.S. In the ASTM E1333 test, boards are pre-conditioned for approximately seven days in a controlled chamber prior to emission testing. The test chamber is purged of HCHO by running tests without boards or with the use of filters designed to lower the background HCHO concentration in air, or both. To run an emission test, the test material is placed inside the conditioned chamber at 25 °C, 50% relative humidity, and an air exchange of 0.5/hr. The sample remains in the chamber for 16 to 20 hours prior to measuring the HCHO concentration of the air in the chamber. In consideration of the proposed numerical values of the Phase 2 standards, manufacturers will likely need to ensure the use of intake air with very low HCHO levels and use the DNPH method to accurately measure HCHO levels in quality control testing.

#### 6. Technical Basis for Consumer Products

Health & Safety Code §41712 requires all consumer product regulations adopted by the Board to be technologically and commercially feasible. Also, 1996 revisions to H&SC §41712 added a constraint that consumer product regulations not eliminate a product form. These statutory criteria were followed in setting the proposed limits for PB and MDF. As discussed in Chapter 1, PB and MDF meet the statutory definition of a "consumer product" under H&SC §41712.

For PB and MDF, there are products already on the market that would comply with the proposed Phase 1 and Phase 2 standards. In this regard, the proposed emission standards for PB and MDF are considered to be technologically feasible as the limit is already being met by at least one product designated as PB or MDF, and that the limit can reasonably be expected to be met in the time frame provided in the proposed ATCM through additional development efforts.

In setting the proposed limits for PB and MDF, staff made an effort, wherever possible, to ensure that multiple resin technologies exist or are anticipated to exist through additional development efforts, which would allow products to comply by the proposed effective dates.

The term “commercially feasible” is not defined in State law. In interpreting this term, staff has utilized the reasoning employed by the U.S. Court of Appeals for the District of Columbia in interpreting the federal Clean Air Act. In the leading case of International Harvester Company v. Ruckelshaus, (D.C. Cir. 1973) 478 F. 2d 615, the Court held that the USEPA could promulgate technology-forcing motor vehicle emission limits which might result in fewer models and more limited choice of engine types for consumers so long as the basic market demand for new passenger automobiles could be generally met.

Following this reasoning, staff has concluded that a regulation is “commercially feasible” as long as the “basic market demand” for a particular consumer product can be met. “Basic market demand” is the underlying need of consumers for a product to fulfill a basic, necessary function. Applying this reasoning to the proposed Phase 2 standards for PB and MDF allows for the basic market demand to be met for each product.

In meeting the criteria for technological and commercial feasibility, we believe that the proposed standards for PB and MDF meet the requirements of H&SC §41712.

## **F. References**

Akzo Nobel. 2005. Kenocatch 4315L. Product information, Casco Adhesives, Sundsvall, Sweden. 2 pp.

Akzo Nobel. 2006. Look at the Possibilities! Presentation by Ulf Odda at the 20 June 2006 Composite Wood Products ATCM Workshop. Accessed: 1 March 2007. From: <http://www.arb.ca.gov/toxics/compwood/odda.pdf>

American National Standards Institute (ANSI). 1994. Medium density fiberboard. Document No. ANSI A208.2-1994. 10 pp.

American National Standards Institute (ANSI). 1999. Particleboard. Document No. ANSI A208.1-1999. 13 pp.

American National Standards Institute, Inc. (ANSI). 2000. American National Standard for Hardwood and Decorative Plywood. Document No. ANSI/HPVA HP-1-2000, Hardwood Plywood and Veneer Association, Reston, VA. 30 pp.

American Society for Testing and Materials (ASTM). 1996. Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber. Designation E1333-96. Annual Book of ASTM Standards, 11.03: 701-712.

Ballerini A, A Despres, and A Pizzi. 2005. Non-toxic, zero emission tannin-glyoxal adhesives for wood panels. Holz als Roh- und Werkstoff, 63: 477-478.

Battelle. 1996. Determination of Formaldehyde and Toluene Diisocyanate Emissions from Indoor Residential Sources. Final Report, CARB Contract No. 93-315, Research Division, Sacramento, CA. 119 pp.

Baumann MGD. 1997. Volatile organic chemical emissions from composite wood products. Technology summary, 8pp. Accessed: 3 May 2002. From: <http://www.fpl.fs.fed.us/documnts/pdf1997/bauma97a.pdf>

Building Center of Japan. 2004. Performance Testing and Evaluation Manual for Emission Rate of Formaldehyde from Building Materials. Document BR-BO-11-02, 10 pp. From: [http://www.bcj.or.jp/en/03/src/SickhouseManual\\_0404.pdf](http://www.bcj.or.jp/en/03/src/SickhouseManual_0404.pdf) Downloaded: 8 November 2006.

CARB. 2003. 2002 Composite Wood Survey Package. Accessed: 18 January 2007. From: <http://www.arb.ca.gov/toxics/compwood/Survey2002.pdf>

Columbia Forest Products. 2006. Purebond™. Product information, Columbia Forest Products, Portland, OR. 2 pp.

Composite Panel Association (CPA). 2006. Welcome to the Composite Panel Association. From: <http://www.pbmdf.com/AboutCPA/index.asp> Accessed: 7 February 2007.

CPA. Not Dated. MDF Producers. Accessed: 8 January 2007. From: <http://www.pbmdf.com/AboutCWC/ProductGuide.asp?PID=1>

Connor AH. 2001. Wood: Adhesives. In: Buschow KHJ (ed). Encyclopedia of Materials: Science and Technology, p. 9583-9599. Elsevier Science Ltd., Amsterdam. ISBN: 0-08-0431526.

Connor AH, LF Lorenz, and KC Hirth. 2002. Accelerated cure of phenol-formaldehyde resins: Studies with model compounds. *Journal of Applied Polymer Science*, 86: 3256-3263.

Cremonini C and A Pizzi. 1999. Field weathering of plywood panels bonded with UF adhesives and low proportions of melamine salts. *Holz als Roh- und Werkstoff*, 57: 318.

Cremonini C, A Pizzi, and P Tekely. 1996. Influence of PMUF resins preparation method on their molecular structure and performance as adhesives for plywood. *Holz als Roh- und Werkstoff*, 54: 85-88.

Deutsches Institut für Bautechnik (DIBt). 1994. Guideline on the classification and control of wood-based panels with regard to formaldehyde emission. Guideline 100, DIBt, Berlin, Germany. (English Translation; Original not seen)

Dunky M. 1995. Wood adhesives: Research and development in Europe. Invited presentation, IUFRO XX World Congress Meeting, 6-12 August 1995, Tampere, Finland. From: <http://www.metla.fi/iufro/iufro95abs/d5pap50.htm>  
Accessed: 7 February 2007.

Eckelman CA. 1997. Brief survey of wood adhesives. FNR 154, Forestry & Natural Resources, Purdue University, Cooperative Extension Service, West Lafayette, IN. 10 pp.

European Panel Federation. Not Dated. Specialty Grades. Accessed: 8 January 2007. From: <http://www.mdf-info.org/technical/t1.html#anchor-thin-23522>

Flakeboard Company Limited. 2005. Product Technical Specifications: Fibrex®. Accessed: 8 January 2007. From: <http://www.flakeboard.com/specs/flakeboard%20product%20technical%20specifications%20-%20fx.pdf>

Franklin International. 1999. Woodworking glues. From: <http://www.titebond.com/IntroPageTB.ASP?UserType=1&ProdSel=FaqTB.asp>  
Accessed: 1 March 2007.

Frihart CR. 2005. Wood adhesion and adhesives. In: Rowell RM (ed). *Handbook of Wood Chemistry and Wood Composites*. Chapter 9, p. 215-278. CRC Press, Inc., Boca Raton.

Frihart CR and JG Chandler. 2006. Can melamine-based wood primers help in understanding bonded wood durability? *Proceedings of the 29<sup>th</sup> Annual Meeting of the Adhesion Society, Inc*, p. 190-192, 19-22 February 2006, Jacksonville, FL.

Groah WJ, J Bradfield, G Gramp, R Rudzinski, and G Heroux. 1991. Comparative response of reconstituted wood products to European and North American test methods for determining formaldehyde emissions. *Environmental Science & Technology*, 25(1): 117-122.

Hardwood Plywood & Veneer Association (HPVA). 2006. Unpublished data; estimated and measured ASTM E1333 test results from selected U.S. hardwood plywood manufacturers.

Heartland Resource Technologies. Not Dated. Technology Page. From: [www.heartlandresource.com/Technology.htm](http://www.heartlandresource.com/Technology.htm) Accessed: 5 February 2007.

Kamoun C, A Pizzi, and M Zanetti. 2003. Upgrading melamine-urea-formaldehyde polycondensation resins with buffering additives. I. The effect of hexamine sulfate and its limits. *Journal of Applied Polymer Science*, 90: 203-214.

Kanji N, C Vijfhuizen, L Artur, and C Braga. 2004. Liberalisation, Gender and Livelihoods: The Mozambique Cashew Nut Case. Summary Report, 28 pp., International Institute for Environment and Development. Accessed: 7 February 2007. From: <http://www.iied.org/pubs/pdf/full/9554IIED.pdf>

Keidel Supply Co., Inc. 2001-2006. Engineered wood for cabinetry. Accessed: 2 February 2007. From: <http://www.keidel.com/design/select/cabinets-matl-eng.htm>

Kim S and H-J Kim. 2004. Evaluation of formaldehyde emission of pine and wattle tannin-based adhesives by gas chromatography. *Holz als Roh- und Werkstoff*, 62: 101-106.

Kim S and H-J Kim. 2005. Comparison of standard methods and gas chromatography method in determination of formaldehyde emission from MDF bonded with formaldehyde-based resins. *Bioresource Technology*, 96: 1457-1464.

Kim S, Y-K Lee, H-J Kim, and HH Lee. 2003. Physico-mechanical properties of particleboards bonded with pine and wattle tannin-based adhesives. *Journal of Adhesion Science & Technology*, 17(14): 1863-1875.

K-State Media Relations & Marketing. 1998. New soy protein adhesive: Water resistant, strong and non-toxic. Accessed: 7 April 2004. From: [www.mediarelations.ksu.edu/WEB/NewsReleases/adhesives8238.html](http://www.mediarelations.ksu.edu/WEB/NewsReleases/adhesives8238.html)

Lei H, A Pizzi, and G Du. 2006. Coreacting PMUF/isocyanate resins for wood panel adhesives. *Holz als Roh- und Werkstoff*, 64: 117-120.

Li K, S Peshkova, and X Geng. 2004. Investigation of soy protein-Kymene® adhesive systems for wood composites. *Journal of the American Oil Chemists' Society*, 81(5): 487-491.

Li J and F Maplesden. 1998. Commercial production of tannins from radiata pine bark for wood adhesives. *IPENZ Transactions*, 25: 46-52.

Lopez-Suevos F and B Riedl. 2003. Effects of *Pinus pinaster* bark extracts content on the cure properties of tannin-modified adhesives and on bonding of exterior grade MDF. *Adhesion Science & Technology*, 17(11): 1507-1522.

Lorenz LF and AC Connor. 2000. Accelerated cure of phenol-formaldehyde by the addition of cure accelerators: Studies with model compounds. Accessed: 7 February 2007. From: <http://www.fpl.fs.fed.us/documnts/pdf2000/loren00b.pdf>

Mansouri HR, A Pizzi, and J-M Leban. 2006. Improved water resistance of UF adhesives for plywood by small pMDI additions. *Holz als Roh- und Werkstoff*, 64: 218-220.

Marra AA. 1992. *Technology of Wood Bonding: Principles in Practice*. Chapter 4, p. 61-101. Van Nostrand Reinhold Company, New York. 454 pp. ISBN: 0442007973.

Milton D. 2007. Lumber and wood industries: Particleboard and oriented strand board. Accessed: 2 February 2007. From: <http://www.thecanadianencyclopedia.com/index.cfm?PgNm=TCE&Params=A1SEC823612>

Mithra S. 2007. What is MDF (Medium Density Fiberboard)? Accessed: 2 February 2007. From: <http://www.wisegeek.com/what-is-mdf.htm>

Myers GE. 1986. Effects of post-manufacture board treatments on formaldehyde emission: A literature review (1960-1984). *Forest Products Journal*, 36(6): 41-51.

Norbord Inc. Not Dated. Hardwood plywood. Accessed: 2 February 2007. From: [http://www.norbord.com/HP\\_EndUses.htm](http://www.norbord.com/HP_EndUses.htm)

Osman Z, A Pizzi, W Kantner, and MC Triboulot. 2005. PUF panel adhesives doped with additional urea and reinforced by isocyanates. *Holz als Roh- und Werkstoff*, 63: 53-56.

Pichelin F, M Nakatani, A Pizzi, S Wieland, A Despres, and S Rigolet. 2006. Structural beams from thick wood panels bonded industrially with formaldehyde-free tannin adhesives. *Forest Products Journal*, 56(5): 31-36.

Pizzi A. 1994. Advanced Wood Adhesives Technology. Chapter 8, p. 273-282. Marcel Dekker, Inc., New York.

Pizzi A. 2000. Tannery row – The story of some natural and synthetic wood adhesives. Wood Science and Technology, 34: 277-316.

Pizzi A. 2006. Recent developments in eco-efficient bio-based adhesives for wood bonding: Opportunities and issues. Journal of Adhesion Science & Technology, 20(8): 829-846.

Pizzi A, R Garcia, and S Wang. 1997. On the networking mechanisms of additives-accelerated phenol-formaldehyde polycondensates. Journal of Applied Polymer Science, 66: 255-266.

Pizzi A, P Tekely, and LA Panamgama. 1996. A different approach to low formaldehyde emission aminoplastic wood adhesives. Holzforschung, 50: 481-485.

Pizzi A, J Valenzuela, and C Westermeyer. 1994. Low formaldehyde emission, fast pressing, pine and pecan tannin adhesives for exterior particleboard. Holz als Roh- und Werkstoff, 52: 311-315.

Pizzi A, E Von Leyser, and C Westermeyer. 1995. Adhesive composition comprising isocyanate phenol-formaldehyde and tannin, useful for manufacturing plywoods for exterior application. U.S. Patent 5407980. Accessed: 27 October 2006. From: <http://www.freepatentsonline.com/5407980.html>

Santana MAE, MGD Baumann, and AH Connor. 1996. Phenol-formaldehyde plywood adhesive resins prepared with liquefied bark of black wattle (*Acacia mearnsii*). Journal of Wood Chemistry and Technology, 16(1): 1-19.

Santana MAE, MGD Baumann, and AH Connor. 1997. Utilization of black wattle bark and tannin liquefied in phenol in the preparation of resol-type adhesives. From: <http://www.fpl.fs.fed.us/documnts/pdf1997/santa97a.pdf> Accessed: 4 February 2007.

Spelter H. 1992. HCHO emissions debate invites scrutiny of lab tests, economics. Panel World, March 1992: 22-24.

Steenbergen S. 2000. Benefits of changing to PVA adhesives. Accessed: 3 June 2006. From: [www.p2pays.org/ref/11/10072.htm](http://www.p2pays.org/ref/11/10072.htm)

Sustainable Design Resources. 2003. Agri-fiber panel manufacturer shares product development lessons. Accessed: 18 January 2007. From: <http://www.greenclips.com/04issues/240.htm>

- Takabatake K. 2003. Japanese Sick House Regulations. Accessed: 6 July 2006. From: <http://strategis.ic.gc.ca/epic/site/imr-ri.nsf/en/gr116049e.html>
- Tomita B and C-Y Hse. 1998. Phenol-urea-formaldehyde (PUF) co-condensed wood adhesives. *International Journal of Adhesion & Adhesives*, 18: 69-79.
- Trosa A and A Pizzi. 2001. A no-aldehyde emission hardener for tannin-based wood adhesives for exterior panels. *Holz als Roh- und Werkstoff*, 59: 266-271.
- Turner S, C Martin, R Hetes, and C Northeim. 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.
- United Soybean Board. 2004. Soy-based composites technical research. From: <http://www.omnitechintl.com/pdf/Composites%20-%20T.pdf> Accessed: 4 February 2007.
- Vazquez G, F Lopez-Suevos, A Villar-Garea, J Gonzalez-Alvarez, and G Antorrena. 2004. <sup>13</sup>C-NMR analysis of phenol-urea-formaldehyde prepolymers and phenol-urea-formaldehyde-tannin adhesives. *Journal of Adhesion Science & Technology*, 18(13): 1529-1543.
- Westcott JM and CR Frihart. 2004. Competitive soybean flour/phenol-formaldehyde adhesives for oriented strandboard. In: Tichy RJ and V Yadama (eds). 38<sup>th</sup> International Wood Composites Symposium Proceedings, p. 199-206. Washington State University, Pullman, WA.
- Wieland S, A Pizzi, S Hill, W Grigsby, and F Pichelin. 2006. The reaction in water of UF resins with isocyanates at short curing times: A <sup>13</sup>C NMR investigation. *Journal of Applied Polymer Science*, 100: 1624-1632.
- Wolcott JJ, WK Motter, NK Daisy, SC Tenhaeff, and WD Detlefsen. 1996. Investigation of variables affecting hot-press formaldehyde and methanol emissions during laboratory production of urea-formaldehyde-bonded particleboard. *Forest Products Journal*, 46(9): 62-68.
- Youngquist JA. 1999. Wood-based composites and panel products. In: Forest Products Laboratory. *Wood Handbook – Wood as an Engineering Material*. Chapter 10. General Technical Report FPL-GTR-113. USDA, Forest Service, Forest Products Laboratory, Madison, WI. 31 pp.
- Zhao C, A Pizzi, and S Garnier. 1999. Fast advancement and hardening acceleration of low-condensation alkaline PF resins by esters and copolymerized urea. *Journal of Applied Polymer Science*, 74: 359-378.

Zheng J. 2002. Studies of PF Resole/Isocyanate Hybrid Adhesives. Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA. 213 pp. Accessed: 4 February 2007. From: [http://scholar.lib.vt.edu/theses/available/etd-01072003-200607/unrestricted/Jun\\_Zheng\\_Dissertation.pdf](http://scholar.lib.vt.edu/theses/available/etd-01072003-200607/unrestricted/Jun_Zheng_Dissertation.pdf)

## **VI. Proposed Airborne Toxic Control Measure (ATCM)**

This chapter describes the proposed ATCM and its basis, including a discussion of alternatives to the proposed ATCM. The staff's proposed regulation order is found in Appendix A.

### **A. Summary of the Proposed Airborne Toxic Control Measure (ATCM)**

The proposed ATCM would reduce HCHO emissions from HWPW, PB, MDF, and finished goods containing those materials, that are sold, offered for sale, supplied, used, or manufactured for sale in California. This would be achieved by requiring manufacturers for the HWPW, PB, and MDF products they produce for use in California, to meet new stringent HCHO emission standards introduced in two phases. The measure applies not only to manufacturers, but also to distributors, importers, fabricators, and retailers that sell or supply HWPW, PB, or MDF, or finished goods containing those materials, for use in California. The proposed ATCM does not apply to composite wood products and finished goods that are manufactured or sold for shipment and use outside of California.

The proposed ATCM also does not apply to PB and HWPW installed in manufactured homes used as dwelling units. Formaldehyde emission standards for PB and plywood installed in manufactured homes have been promulgated by the U.S. Department of Housing and Urban Development (24 Code of Federal Regulations section 3280 et seq., section 3280.308). Federal law generally preempts State and local regulations regarding construction and safety standards for manufactured homes, such as the formaldehyde standards specified in the HUD regulations (see 42 U.S. C.A section 94503(d)). To comply with federal law, the proposed ATCM exempts products covered by the HUD regulations. The HUD regulations do not apply to plywood and particleboard used in applications other than manufactured homes (e.g., residential and office buildings, furniture, etc.) and finished products made with these materials. The HUD regulations also do not apply to MDF used in manufactured homes, which would be covered by the proposed ATCM.

Furthermore, the proposed ATCM would not apply to architectural plywood, military specification plywood used in airplane construction, or composite wood products used in motor vehicles. Military plywood and composite wood use in motor vehicles is very limited and inclusion in the regulation would create difficult compliance issues for these mobile sources. Finally, the proposed ATCM also exempts finished windows containing less than five volume percent of HWPW, PB or MDF combined in relation to the total volume of the finished window product.

On January 1, 2009, the proposed ATCM establishes a suite of new emission standards that would take effect, beginning with the Phase 1 (P1) emission standards for HWPW made with a veneer core (HWPW-VC), PB, MDF, and thin

MDF (Table VI-1). Subsequently, on July 1, 2009, the remaining P1 standard for HWPW made with a composite core (HWPW-CC) would become effective. The Phase 2 (P2) standards for HWPW-VC, PB, MDF, thin MDF, and HWPW-CC become effective in the 2011-2012 timeframe, as specified in the following table.

Table VI-1. Proposed Phase 1 and Phase 2 Standards for Hardwood Plywood (HWPW), Particleboard (PB), and Medium Density Fiberboard (MDF) <sup>1</sup> Bookmark not defined.					
Effective Date	----- ASTM E1333-96 Value (ppm) -----				
	HWPW-VC	HWPW-CC	PB	MDF	tMDF
January 2009	P1: 0.08	-----	P1: 0.18	P1: 0.21	P1: 0.21
July 2009	-----	P1: 0.08	-----	-----	-----
January 2011	P2: 0.05	-----	P2: 0.09	P2: 0.11	-----
January 2012	-----	-----	-----	-----	P2: 0.13
July 2012	-----	P2: 0.05	-----	-----	-----

(<sup>1</sup>) Abbreviations: P1 = Phase 1, P2 = Phase 2, HWPW-VC = HWPW with a veneer core, HWPW-CC = HWPW with a composite core, PB = particleboard, MDF = medium density fiberboard; tMDF = thin MDF.

Finally, the proposed ATCM contains “sell-through” provisions that allow noncomplying products manufactured before the effective dates of the Phase 1 and Phase 2 emission standards to be sold for certain specified time periods after these effective dates. Differing sell-through periods apply depending on whether the product is sold by a manufacturer, distributor, importer, fabricator, or retailer. All of the sell-through provisions of the ATCM are contained in Appendix 1 of section 93120.12.

**1. Section 93120.3- Requirements for Manufacturers of Composite Wood Products**

The requirements for manufacturers are contained in section 93120.3 and Appendix 2 of section 93120.12. In general, manufacturers of HWPW-VC, HWPW-CC, PB, MDF, or thin MDF, whether foreign or domestic, would be required to:

- Meet the applicable emission standards;
- Provide independent verification of the emissions performance of the composite wood product they manufacture;
- Have quality assurance programs;
- Comply with labeling and recordkeeping requirements.

To independently verify the emissions performance of their composite wood products, manufacturers using formaldehyde based resin systems would be

required to be monitored by independent groups known as “third party certifiers.” Manufacturers would work with third party certifiers to initiate quality control and emission testing programs in order to demonstrate ongoing compliance with the applicable emission standards in Table VI-1. All testing will be correlated to product emission tests using the “large chamber test method,” hereafter referred to as ASTM E1333-96.

Under the provisions of section 93120.12, Appendix 2, manufacturers would also be required to develop and follow a quality assurance program. Basic elements of the quality assurance program include development of a quality control manual, verification of quality control personnel, establishment of a correlation between the manufacturing plant test method and ASTM E1333-96, and ongoing quarterly emissions correlation verification testing. In addition, Appendix 2 also provides guidance on the disposition of manufactured panels that do not meet the regulatory emission standards.

Generally speaking, the proposed regulation primarily affects composite wood products made with formaldehyde based resin systems. As mentioned throughout this staff report, however, several examples exist today of alternative resin systems that contain no added formaldehyde and result in only de minimus formaldehyde emissions from composite wood products. Therefore, under section 93120.3(b) manufacturers using these resins would be allowed to follow an alternative compliance option that does not require third party certification.

To qualify for the “no added formaldehyde resin” compliance option, manufacturers must apply to and obtain written approval from CARB. The application must contain the resin chemical formulation, a demonstration of the emissions performance of the candidate “no added formaldehyde” resin system, and a statement to indicate the manufacturer’s intent to use the candidate resin exclusively in the manufacturing of identified products. Upon approval, CARB will notify the manufacturer in writing. CARB approval would exempt the manufacturer only from the third party certification requirements of the proposed ATCM; all other ATCM requirements would still apply.

Because composite wood panels are a commonly traded commodity, there are many potential distribution routes within commerce. So, to facilitate enforcement of the emission standards the proposed ATCM requires all manufacturers that supply products for sale or use in California to label these products in a manner that clearly identifies their third party certifier, the name of their company, product lot number or batch produced, and a marking to denote that the product meets the applicable Phase 1 or Phase 2 emission standard. Manufacturers are also required to maintain records for two years so composite wood products can be traced back to individual manufacturers and to specific emissions performance tests under third party certification program.

Because manufacturers are the only group who can determine the formaldehyde levels in composite wood products, it is vital that downstream customers have some way of knowing whether the products they purchase are legal to sell in California. Therefore, the proposed ATCM specifies the information that must be passed from manufacturers to downstream customers. In addition to the labeling requirements discussed above, manufacturers are required to state on the product bill of lading or invoice that the product complies with the applicable Phase 1 or Phase 2 emission standard. Manufacturers are also required to maintain specified records at their production facilities. These records will allow individual panels sold in commerce to be traced back to specific lot or batch of product that was manufactured.

The proposed ATCM allows a one-month sell-through period for noncomplying products manufactured before the effective dates of the Phase 1 and Phase 2 standards. The specific sell-through dates for manufacturers are set forth in the following table (Table VI-2):

Table VI-2. Schedule of Composite Wood Product Sell-through for Manufacturers <sup>1</sup>					
Event	HWPW-VC	HWPW-CC	PB	MDF	tMDF
Effective Date: P1	Jan '09	Jul '09	Jan '09	Jan '09	Jan '09
Date When Only P1 Products Can Be Sold	Feb '09	Aug '09	Feb '09	Feb '09	Feb '09
Effective Date: P2	Jan '11	Jul '12	Jan '11	Jan '11	Jan '12
Date When Only P2 Products Can Be Sold	Feb '11	Aug '12	Feb '11	Feb '11	Feb '12

(<sup>1</sup>) All effective dates begin on the 1<sup>st</sup> day of the specified month-year. Manufacturers have a one-month sell-through period following the effective date of the applicable P1 or P2 standard. Abbreviations: P1 = Phase 1, P2 = Phase 2, HWPW-VC = HWPW with a veneer core, HWPW-CC = HWPW with a composite core, PB = particleboard, MDF = medium density fiberboard, tMDF = thin MDF.

Relative to enforcement, section 93120.3(f) notifies manufacturers that they may be inspected by CARB or local air district personnel (as well as third party certifiers as specified in Appendices 2 and 3 of section 93120.12). Inspections would be focused on facility inspections, auditing of records, and securing of samples for enforcement testing.

## **2. Section 93120.4- Requirements for Third Party Certifiers**

Third party certifiers have an important role in ensuring that manufacturers of composite wood products can demonstrate that their production facilities are producing products that comply with the applicable emission standards in Table VI-1. Requirements for third party certifiers are contained in section 93120.12, Appendix 3. The application process to become an ARB-approved third party certifier is specified in section 93120.4.

The proposed ATCM requires routine quality assurance emissions testing by manufacturers of newly produced composite wood products. The quality assurance manufacturing testing program is developed in collaboration with, and is independently validated by, third party certifiers. All third party certifiers are required to be approved by CARB as provided in section 93120.4.

To be approved as a third party certifier, an organization must submit an application in writing to the Executive Officer for approval. Applicants must demonstrate that they have actual field experience in the certification of laboratories and wood products, have the ability to train and supervise inspectors, possess product inspection agency certification, and large chamber ASTM E1333-96 certification by the International Accreditation Service or by another signatory to the International Laboratory Accreditation Cooperation Mutual Recognition Arrangement, and must list which products they are qualified to certify. If the criteria specified in the ATCM are met, the Executive Officer will issue an executive order approving them as a third party certifier. The Executive Officer will also assign an identifying number to each third party certifier. As described previously, manufacturers will display this number on each panel or bundle of composite wood products.

The proposed ATCM requires third party certifiers to take part in quarterly validation of correlations between manufacturers' small scale testing and the ASTM E1333-96 large chamber. All large chambers must be certified by the International Accreditation Service, Inc., or by another signatory to the International Laboratory Accreditation Cooperation Mutual Recognition Arrangement. Third party certifiers must also conduct periodic inspections of manufacturing facilities and maintain records for two years, including a list of manufacturers certified by the third party certifier, results of inspection audits, and proof of certification for ASTM E1333-96 large chambers used.

Third party certifiers are also subject to enforcement audits by CARB. Executive orders granted to third party certifiers will contain conditions allowing CARB to verify that third party certifiers are complying with all regulatory requirements. A provision is also included whereby the Executive Officer may review and, for good cause, modify or revoke an executive order approving a third party certifier. In order to provide due process protections, an executive order cannot be

modified or revoked unless the third party certifier is first provided an opportunity for a hearing.

### 3. Section 93120.5- Requirements for Distributors

Distributors are the “goods movers” within the marketplace supply chain. The proposed ATCM requires that all products and finished goods sold by distributors must comply with the applicable emission standards. The proposed ATCM also requires that distributors must take reasonable prudent precautions to ensure that the composite wood products and finished goods they acquire are in compliance with the applicable emission standards in Table VI-1. To accomplish this, distributors would need to establish a procurement policy that requires them to obtain and keep a record of written documentation from their suppliers that the products they acquire meet the applicable emission standards. Records must be kept for a minimum of two years for enforcement purposes.

Typically distributors only sell products in commerce and do not modify the products they sell. But, if a distributor modifies the composite wood products or finished goods that they acquire, then the regulation requires distributors to follow the labeling and sell-through requirements for fabricators (see section VI.A.5).

Under section 93120.5(d), distributors are also required to provide a written statement on the bill of lading or invoice that states that the composite wood product or finished goods they sell meet the emission standards.

Because distributors may purchase HWPW-VC, HWPW-CC, PB, MDF or tMDF panels from manufacturers during the sell-through periods in Table VI-2, an additional period of time is provided to distributors to sell-through products that do not comply with the new standards. In total, distributors would have a sell-through period of five-months after the effective date of the applicable Phase 1 or Phase 2 standards in Table VI-1 (see Table VI-3). The sell-through period for finished goods would be the same as that for composite wood products.

Event	HWPW-VC	HWPW-CC	PB	MDF	tMDF
Effective Date: P1	Jan '09	Jul '09	Jan '09	Jan '09	Jan '09
Date When Only P1 Products Can Be Sold	Jun '09	Dec '09	Jun '09	Jun '09	Jun '09
Effective Date: P2	Jan '11	Jul '12	Jan '11	Jan '11	Jan '12
Date When Only P2 Products Can Be Sold	Jun '11	Dec '12	Jun '11	Jun '11	Jun '12

(<sup>1</sup>) All effective dates begin on the 1<sup>st</sup> day of the specified month-year. Distributors have a five-month sell-through period following the effective date of the applicable P1 or P2 standard. Abbreviations: P1 = Phase 1, P2 = Phase 2, HWPW-VC = HWPW with a veneer core, HWPW-CC = HWPW with a composite core, PB = particleboard, MDF = medium density fiberboard, tMDF = thin MDF.

Regarding enforcement, section 93120.5(e) notifies distributors that they may be inspected by CARB or local air district personnel. Inspections would be focused on facility inspections, auditing of records, and securing of samples for enforcement testing.

#### **4. Section 93120.6- Requirements for Importers**

The proposed ATCM requires that all products and finished goods sold by importers must comply with the applicable emission standards. The proposed ATCM also requires that importers must take reasonable prudent precautions to ensure that the composite wood products and finished goods they acquire are in compliance with the applicable emission standards in Table VI-1. To accomplish this, importers would need to establish a procurement policy that requires them to obtain and keep a record of written documentation from their suppliers that the products they acquire meet the applicable emission standards. Records must be kept for a minimum of two years for enforcement purposes.

Typically, importers do not modify goods they market, so for unmodified composite wood products or finished goods, no additional labeling would be required on the part of importers. However, if an importer modifies the composite wood products or finished goods that they purchase, they would be subject to the labeling and sell-through requirements for fabricators (see section VI.A.5).

Under section 93120.6(d), importers are also required to provide a written statement on the bill of lading or invoice that states that the composite wood product or composite wood products contained in finished goods comply with the emission standards in Table VI-1.

Because importers may purchase HWPW-VC, HWPW-CC, PB, MDF, or tMDF panels and finished goods from an overseas manufacturer during the sell-through periods allowed for manufacturers, an additional period of time is provided to importers to sell-through products that do not comply with the new standards. In total, importers would have a sell-through period of five months (the same as distributors) after the effective date of the applicable Phase 1 or Phase 2 standards in Table VI-1 (see Table VI-3). The sell-through period for finished goods would be the same as that for composite wood products.

Table VI-4. Schedule of Composite Wood Product Sell-through for Importers <sup>1</sup>					
Event	HWPW-VC	HWPW-CC	PB	MDF	tMDF
Effective Date: P1	Jan '09	Jul '09	Jan '09	Jan '09	Jan '09
Date When Only P1 Products Can Be Sold	Jun '09	Dec '09	Jun '09	Jun '09	Jun '09
Effective Date: P2	Jan '11	Jul '12	Jan '11	Jan '11	Jan '12
Date When Only P2 Products Can Be Sold	Jun '11	Dec '12	Jun '11	Jun '11	Jun '12

(<sup>1</sup>) All effective dates begin on the 1<sup>st</sup> day of the specified month-year. Importers have a five-month sell-through period following the effective date of the applicable P1 or P2 standard. Abbreviations: P1 = Phase 1, P2 = Phase 2, HWPW-VC = HWPW with a veneer core, HWPW-CC = HWPW with a composite core, PB = particleboard, MDF = medium density fiberboard, tMDF = thin MDF.

Regarding enforcement, section 93120.6(e) notifies importers that they may be inspected by CARB or local air district personnel. Inspections would be focused on facility inspections, auditing of records, and securing of samples for enforcement testing.

**5. Section 93120.7- Requirements for Fabricators**

The proposed ATCM defines “fabricator” as any person that uses composite wood products to make finished goods. Examples of fabricators are companies that use composite wood panels to produce furniture or cabinets. While such companies might be referred to as “manufacturers” in ordinary conversation, they are not “manufacturers” under the ATCM. The proposed ATCM uses the term “manufacturer” to refer only to persons who manufacturer or produce the actual composite wood products (i.e., HWPW, PB or MDF), as opposed to persons who use panels of HWPW, PB or MDF to make finished goods. A person can be both a “fabricator” and a “manufacturer” if they produce both composite wood products and make finished goods from these products. Such a person would have to comply with both the provisions of the ATCM that apply to manufacturers (for the HWPW, PB or MDF that they produce) and the provisions that apply to fabricators (for the finished goods that they produce).

Like distributors and importers, the proposed ATCM requires that all products and finished goods sold by fabricators must comply with the applicable emission standards. The proposed ATCM also requires that fabricators must take reasonable prudent precautions to ensure that the composite wood products and finished good components they acquire are in compliance with the applicable emission standards in Table VI-1. To accomplish this, fabricators would need to

establish a procurement policy that requires them to obtain and keep a record of written documentation from their suppliers that the products they acquire meet the applicable emission standards. Records must be kept for a minimum of two years for enforcement purposes.

Among finished goods produced with composite wood products, window assemblies typically utilize only small amounts of HWPW, PB or MDF. Therefore, exposure from composite wood products used in windows is expected to be insignificant and enforcement testing would also be complex and expensive. Therefore, section 93120.7(b) provides an exemption for windows. The exemption applies only to windows that contain more than five percent by volume of any composite wood product.

To denote that the finished goods produced by a fabricator for the California market were made with complying products, fabricators must label every finished good, or on every box containing finished goods. Fabricators may label finished goods with a stamp, tag, sticker, or bar code. Under the proposal, fabricators would also be required to designate their goods as being made with HWPW, PB or MDF in compliance with the emission standards on the bill of lading or invoice provided to retailers or other entities that sell those composite wood products or finished goods to the public.

Because fabricators may purchase HWPW-VC, HWPW-CC, PB, MDF, or tMDF from distributors and importers during the sell-through periods allowed for these entities, an additional period of time is provided to fabricators to sell-through products that do not comply with the new standards. In total, fabricators would have a sell-through period of 12 months after the effective date of the applicable Phase 1 or Phase 2 standards (see Table VI-5). The longer sell-through period reflects that fact that it takes time for fabricators to produce finished goods from the composite wood products they purchase.

Event	HWPW-VC	HWPW-CC	PB	MDF	tMDF
Effective Date: P1	Jan '09	Jul '09	Jan '09	Jan '09	Jan '09
Date When Only P1 Products Can Be Sold	Jan '10	Jul '10	Jan '10	Jan '10	Jan '10
Effective Date: P2	Jan '11	Jul '12	Jan '11	Jan '11	Jan '12
Date When Only P2 Products Can Be Sold	Jan '12	Jul '13	Jan '12	Jan '12	Jan '13

(<sup>1</sup>) All dates begin on the 1<sup>st</sup> day of the specified month-year. Fabricators are provided a 12-month sell-through period following the effective date of the applicable P1 or P2 standard. Abbreviations: P1 = Phase 1, P2 = Phase 2, HWPW-VC = HWPW with a veneer core, HWPW-CC = HWPW with a composite core, PB = particleboard, MDF = medium density fiberboard, tMDF = thin MDF.

Regarding enforcement, section 93120.7(e) notifies fabricators that they may be inspected by CARB or local air district personnel. Inspections would be focused on facility inspections, auditing of records, and securing of samples for enforcement testing.

## **6. Section 93120.8- Requirements for Retailers**

The proposed ATCM requires that all products and finished goods sold by retailers must comply with the applicable emission standards. The proposed ATCM also requires that retailers must take reasonable prudent precautions (such as communicating with their suppliers) to ensure that the composite wood products and finished goods they purchase are in compliance with the applicable emission standards in Table VI-1. To accomplish this, retailers would need to establish a procurement policy that requires them to obtain and keep a record of written documentation from their suppliers that the products they acquire meet the applicable emission standards. Records must be kept for a minimum of two years for enforcement purposes.

Because retailers may purchase HWPW-VC, HWPW-CC, PB, MDF or tMDF products or finished goods from manufacturers, importers, distributors, or fabricators during the sell-through periods for these entities, an additional period of time is provided to retailers to sell-through products that do not comply with the new standards. In total, retailers would have sell-through periods of 12 months and 18 months, after the effective date of the applicable Phase 1 or Phase 2 standards in Table VI-1 (see Table VI-6), for HWPW-VC, HWPW-CC, PB, MDF, and tMDF panels and finished goods containing those products, respectively.

Table VI-6. Schedule of Composite Wood Panel Sell-through for Retailers <sup>1</sup>					
Event	HWPW-VC	HWPW-CC	PB	MDF	tMDF
<b>A. Composite Wood Products</b>					
Effective Date: P1	Jan '09	Jul '09	Jan '09	Jan '09	Jan '09
Date When Only P1 Products Can Be Sold	Jan '10	Jul '10	Jan '10	Jan '10	Jan '10
Effective Date: P2	Jan '11	Jul '12	Jan '11	Jan '11	Jan '12
Date When Only P2 Products Can Be Sold	Jan '12	Jul '13	Jan '12	Jan '12	Jan '13
<b>B. Finished Goods</b>					
Effective Date: P1	Jan '09	Jul '09	Jan '09	Jan '09	Jan '09
Date When Only P1 Products Can Be Sold	Jul '10	Jan '11	Jul '10	Jul '10	Jul '10
Effective Date: P2	Jan '11	Jul '12	Jan '11	Jan '11	Jan '12
Date When Only P2 Products Can Be Sold	Jul '12	Jan '14	Jul '12	Jul '12	Jul '13
<p><sup>(1)</sup> All effective dates begin on the 1<sup>st</sup> day of the specified month-year. Retailers have a 12-month or 18-month sell-through period following the effective date of the applicable P1 or P2 standard for panels or finished products, respectively. Abbreviations: P1 = Phase 1, P2 = Phase 2, HWPW-VC = HWPW with a veneer core, HWPW-CC = HWPW with a composite core, PB = particleboard, MDF = medium density fiberboard, tMDF = thin MDF.</p>					

Regarding enforcement, section 93120.8(c) notifies retailers that they may be inspected by CARB or local air district personnel. Inspections would be focused on facility inspections, auditing of records, and securing of samples for enforcement testing..

## **7. Section 93120.9- Test Methods**

The regulation includes various test methods to be used to demonstrate compliance with the emissions standards specified in section 93120.2.

Under section 93120.9(a), the emission standards will be based on the industry standard large chamber test method, as specified in American Standards for Testing and Materials (ASTM) E1333-96. The ASTM E1333-96 test method was developed by the ASTM through a consensus process and is recognized as the “gold standard” among formaldehyde test methods. Furthermore, the current federal HUD standards regarding particleboard and plywood in manufactured homes specify the ASTM E1333-96 as the applicable test method.

Sections 93120.9(a)(1)-(3) allows for the use of equivalent alternate test methods in lieu of ASTM E1333-96, if approved by the Executive Officer. An application process is also specified for obtaining ARB approval. This section allows alternative test methods to be used that may prove to be more applicable to particular products.

Sections 93120.9(b) and (c) describe the test method to be used for enforcement purposes. These provisions reference the use of ASTM D6007-02 for testing of HWPW, PB or MDF, or finished goods made from these materials. The ASTM D6007-02 is a standardized small chamber industry-developed test method. When properly calibrated, test results from a small chamber are known to have a very high correlation to large chamber test results. The use of the small chamber is included in the regulation to allow CARB to conduct compliance verification testing using smaller sample sizes and to obtain faster results.

The small chamber method will also allow CARB to test pieces of composite wood products in finished goods that are bare or partially covered (e.g. one side laminated). To test fully covered or laminated finished products, CARB will follow the method development plan shown in Table VI-7.

Table VI-7. Development Plan for Fully Covered Finished Products	
Timeframe	Action/Activity
Spring 2007	<ul style="list-style-type: none"> <li>• Purchase lab equipment</li> <li>• Purchase/build small testing chambers</li> <li>• Begin evaluating field equipment</li> </ul>
Summer 2007	<ul style="list-style-type: none"> <li>• Develop draft lab analytical methods and begin testing composite wood samples, starting with raw boards</li> <li>• Begin certification process for small chambers</li> </ul>
Fall 2007	<ul style="list-style-type: none"> <li>• Begin evaluating finished product sample preparation approaches</li> </ul>
Late 2007	<ul style="list-style-type: none"> <li>• Complete certification of small chambers against a large chamber</li> <li>• Begin round robin testing with other labs</li> </ul>
Spring 2008	<ul style="list-style-type: none"> <li>• Complete round robin testing, make refinements to lab methods as necessary</li> </ul>
Summer 2008	<ul style="list-style-type: none"> <li>• Complete lab analytical protocols, including finished product testing (sampling, preparation and analysis</li> </ul>

**B. Alternatives to the Proposed Airborne Toxic Control Measure**  
Bookmark not defined.

**1. Alternative 1: No Action**

Taking no action would allow the continued sale of high HCHO-emitting composite wood products that have detrimental impacts on public health. Without stricter HCHO emission limits it will continue to be legal for high HCHO-emitting composite wood products and finished goods to be sold in California that cannot currently be sold to many other countries. Because there is no safe threshold for exposure to HCHO, taking no action perpetuates the existing public health risks described in this staff report.

**2. Alternative 2: Establish Less Stringent Emission Limits**

a. Applicability

The principal entities that would be affected by this alternative are manufacturers of HWPW-VC, HWPW-CC, PB, MDF, and tMDF, resin manufacturers, businesses that use those materials to fabricate other products, distributors, importers and retailers of HWPW-VC, HWPW-CC, PB, MDF, tMDF, or finished goods containing those materials.

b. Effectiveness

This alternative would not provide as great a public health benefit as the proposed ATCM. For example, if emission standards equal to the 1985 HUD standards are promulgated, there would be no public health benefit relative to current conditions because the major portion of U.S. manufacturers already produce composite wood products in voluntary compliance with the HUD standard. Some reductions may be achieved with respect to emissions from MDF, which is currently an unregulated product.

c. Enforceability

This alternative would require the same level of enforcement as the proposed ATCM.

d. Resource Considerations

Minor modifications may be needed to incorporate a greater compliance margin to ensure that only products meeting an emission standard equal to the HUD standard are distributed to California. Tighter tolerances on manufacturing lines may need to be established by some manufacturers in order to avoid potential violations resulting from the sale of non-complying products.

**3. Alternative 3: Establish More Stringent Emission Limits – Zero Emission Products**

This alternative would require composite wood manufacturers to use no added HCHO resins in the production of HWPW-VC, HWPW-CC, PB, MDF, and thin MDF.

a. Applicability

Manufacturers of HWPW-VC, HWPW-CC, PB, MDF, thin MDF; resin producers; businesses that use composite wood products to fabricate other products; distributors; importers; and retailers of HWPW-VC, HWPW-CC, PB, MDF, thin MDF, or finished goods containing those materials, would be the principal entities affected.

b. Effectiveness

This alternative is not feasible at present, as we believe that cost-effective, no added HCHO resins would not be commercially available for all three products in the 2011-2012 timeframe. Setting a “zero emission” cap standard is also technically impractical because some HCHO is emitted from wood itself, and the air used to measure HCHO emissions from composite wood panels also contains trace amounts of HCHO. As such, even if the product were made with a no added HCHO resin, there could be enough HCHO emitted from wood or present in the test intake air to result in a non-zero emission test value.

c. Enforceability

This alternative would require the same level of enforcement as the proposed ATCM.

d. Resource Considerations

Major breakthroughs in manufacturing and resin technology would be needed to consistently produce HWPW, PB, and MDF that would comply with a zero emission standard. The costs for developing these products would far exceed the estimated cost increases resulting from the proposed ATCM, possibly as much as 135% higher in the case of zero emission MDF made with pMDI.

**C. Conclusion**

We evaluated each of the alternatives and determined that the alternatives did not meet the objective of H&SC §39666 to reduce emissions to the lowest level achievable through the application of BACT, or a more effective control method, in consideration of cost, health risk, and environmental impacts.

## **VII. Health Impacts of the Proposed Airborne Toxic Control Measure**

This chapter presents an overview of the health risk assessment process, potential health impacts from exposure to HCHO in selected scenarios, information on alternative wood adhesives, and the benefits of the proposed ATCM in terms of reducing statewide emissions and potential health impacts.

### **A. Overview of the Health Risk Assessment**

A health risk assessment (HRA) is a report prepared by a risk assessor that describes the potential for an individual or population to experience adverse health impacts as a result of being exposed to the emissions released from a pollution-generating facility. Adverse health effects may include cancer, developmental effects, and/or respiratory illness. In a HRA, estimates of total pollutant exposure are calculated by cumulating pollutant uptake via inhalation of gaseous and/or particulate compounds, ingestion of contaminated water and food, and dermal absorption. For HCHO emitted by building materials and consumer products, the principal pollutant uptake pathway is inhalation of gaseous HCHO. In the following HRA, HCHO uptake via inhalation was the only exposure pathway evaluated to assess potential cancer or non-cancer health impacts.

The following four steps are followed to prepare a HRA:

- Step 1 -- Hazard Identification

First, a determination is made as to whether or not a hazard exists. If a hazard is deemed to exist, an analysis is performed to identify which pollutant(s) is/are involved and what types of health effects may result (i.e., cancer or non-cancer). As HCHO has been identified as a toxic air contaminant (CARB, 1992), there is no threshold exposure level below which adverse health effects are not anticipated.

- Step 2 -- Dose-response Assessment

Next, the relationship, if any, between an individual's exposure to a pollutant and the incidence of adverse health effects is characterized. For cancer and non-cancer effects, OEHHA provides cancer potency or unit risk factors (URF) and reference exposure levels (REL), respectively. The following citations contain lists of the URFs or RELs used in California:

OEHHA. 2005a. Appendix A: Hot Spots Unit Risk and Cancer Potency Values. In: OEHHA. Air Toxics Hot Spots Program Risk Assessment Guidelines. Part II. Technical Support Document for Describing Available Cancer Potency Factors.

OEHHA. 2000. All acute reference exposure levels adopted by OEHHA as of May 2000. From: [http://www.oehha.ca.gov/air/acute\\_rels/allacreels.html](http://www.oehha.ca.gov/air/acute_rels/allacreels.html)

OEHHA. 2005b. All chronic reference exposure levels adopted by OEHHA as of February 2005. From: [http://www.oehha.ca.gov/air/chronic\\_rels/allchcrels.html](http://www.oehha.ca.gov/air/chronic_rels/allchcrels.html)

- Step 3 – Exposure Assessment

Public exposure is estimated by evaluating representative and elevated exposure scenarios, relevant exposure pathways (e.g., inhalation), and the magnitude of exposure. For exposure to HCHO, daily time-weighted average exposures were calculated for children and adults, by estimating the time spent either outdoors, indoors, or and in-vehicles, and multiplying by an applicable representative or elevated HCHO concentration from the literature.

- Step 4 – Risk Characterization

To calculate potential cancer risk in adults and children, the Hot Spots Program equation (OEHHA, 2003) was used to determine an inhalation dose ( $Dose_{inh}$ ) for HCHO:

$$Dose_{inh} = [(C_{air}) \times (DBR) \times (A) \times (EF) \times (ED) \times 10^{-6}] \div AT$$

Where:

$Dose_{inh}$	= Dose through inhalation (mg/kg body weight-day)
$C_{air}$	= HCHO concentration in air ( $\mu\text{g}/\text{m}^3$ )
DBR	= Daily breathing rate (liter/kg body weight-day)
A	= Inhalation absorption factor (dimensionless adjustment)
EF	= Exposure frequency (days/year)
ED	= Exposure duration (years)
$10^{-6}$	= Constant: ( $10^{-3} \times 10^{-3}$ ) for ( $\mu\text{g}$ to $\text{mg}$ ) and (liter to $\text{m}^3$ ), respectively
AT	= Averaging time period (70-years) in days (25,550 days)

The numerical values of the components in the above equation were chosen based on OEHHA (2003), except for the calculation of  $C_{air}$ . For this component, a daily time-weighted average (TWA) formaldehyde concentration was calculated, consistent with the scenario-based guidelines for exposure assessment developed by USEPA (Federal Register, 1992). A daily TWA formaldehyde concentration was calculated separately for adults and children. In general terms, daily TWA HCHO concentration is:

$$\text{Daily TWA} = [(T_{ind} \times C_{ind}) + (T_{out} \times C_{out}) + (T_{inv} \times C_{inv})] \div 24$$

Where:

Daily TWA	= Daily time-weighted average HCHO concentration ( $\mu\text{g}/\text{m}^3$ )
$T_{\text{ind}}$	= Time spent indoors (hr)
$C_{\text{ind}}$	= Indoor HCHO concentration ( $\mu\text{g}/\text{m}^3$ )
$T_{\text{out}}$	= Time spent outdoors (hr)
$C_{\text{out}}$	= Outdoor HCHO concentration ( $\mu\text{g}/\text{m}^3$ )
$T_{\text{inv}}$	= Time spent in-vehicles (hr)
$C_{\text{inv}}$	= In-vehicle HCHO concentration ( $\mu\text{g}/\text{m}^3$ )
24	= Constant (24 hr/day)

A reference exposure level or “REL” is used as an indicator of the potential for a compound to cause adverse, non-cancer health effects (e.g., respiratory illness). For a given TAC, its REL is the pollutant concentration at or below which no adverse health effects are anticipated. To incorporate a margin of safety into RELs, they are designed to protect the most sensitive individuals in a population from acute and chronic exposures to a TAC. An acute exposure is defined as one or a series of short-term exposures generally lasting less than 24 hours (i.e., a one hour exposure is used to assess acute non-cancer impacts). Chronic exposures are defined as exposures lasting from one year to an entire lifetime.

## **B. Total Daily Formaldehyde Exposure as the Basis for Risk Assessment**

To assess the potential health impacts of HCHO emissions from composite wood products, quality assured data are needed on HCHO concentrations that people are exposed to, and health effect values (i.e., URFs and RELs). For this rulemaking, a persons’ total daily exposure to HCHO was estimated; this is a measure of cumulative HCHO exposure from the air they breathe in indoor, outdoor, and in-vehicle microenvironments, rather than outdoor air alone. This requires estimates to be calculated of average HCHO concentrations in three microenvironments that people spend time in. As studies have found that Californians spend 90% or more of their time indoors, a principal focus was the development of estimates for HCHO concentrations in new and existing homes. Brief descriptions are provided in the following subchapters concerning the estimates of indoor HCHO concentrations and health effects values.

### **1. Average and Elevated Formaldehyde Concentrations**

Average and elevated HCHO concentration data were primarily obtained from a CARB report prepared for the Legislature on indoor air pollution in California (CARB, 2005). In Appendix III of the report, average and maximum HCHO concentrations in selected indoor and outdoor microenvironments were estimated (Table VII-1) and served as the principal basis for calculating daily TWA concentrations of HCHO. For conventional homes, the elevated concentration represents the average concentration measured in newly built

homes (Sherman and Hodgson, 2003). The average and elevated HCHO concentrations for time spent in vehicles were estimated from the data in Research Triangle Institute (1998).

Table VII-1. Average and Elevated Formaldehyde Concentrations ( $\mu\text{g}/\text{m}^3$ ) in Selected Indoor and Outdoor Microenvironments		
Microenvironment	Average ( $\mu\text{g}/\text{m}^3$ )	Elevated ( $\mu\text{g}/\text{m}^3$ )
Conventional Home	17.2	46.7
In-vehicle	9.6	12.0
Outdoors	3.7	15.0

(<sup>1</sup>) Sources: CARB (2005); Research Triangle Institute (1998); Sherman and Hodgson (2003).

## 2. Health Effects Values for Formaldehyde

Pollutant exposure-response relationships are characterized by a variety of health effects values that describe the incidence of adverse health effects relative to the degree of pollutant exposure. A unit risk factor or “URF” is used as an estimate of potential cancer risk, and RELs are used as estimates of potential non-cancer impacts. The health values for HCHO, determined by OEHHA, are listed in Table VII-2. For non-cancer effects, the RELs (acute and chronic) were established to protect against eye irritation, and associated impacts to the respiratory and immune systems (OEHHA, 1999; 2000).

Table VII-2. Health Effects Values for Formaldehyde <sup>1</sup>		
Unit Risk Factor ( $\mu\text{g}/\text{m}^3$ ) <sup>-1</sup>	Acute Reference Exposure Level ( $\mu\text{g}/\text{m}^3$ )	Chronic Reference Exposure Level ( $\mu\text{g}/\text{m}^3$ )
$6 \times 10^{-6}$	94	3

(<sup>1</sup>) Sources: OEHHA (2000); (2005a); (2005b).

### a. Health Effects in Humans

Numerous acute controlled human exposure studies, as well as observational studies in occupational settings, have been conducted to investigate formaldehyde’s irritative and pulmonary effects (Sheppard et al., 1984; Sauder et al., 1986; Schachter et al., 1986; Kulle et al., 1987; Sauder et al., 1987; Schachter et al., 1987; Witek et al., 1987; Uba et al., 1989; Harving et al., 1990; Akbar-Khanzadeh et al., 1994). Both irritation and significant decrements in pulmonary function have been observed in occupational studies of carpentry,

wood and wood product, chemical plant, and formaldehyde production plant workers exposed to formaldehyde (Alexandersson et al., 1982; Alexandersson and Hedenstierna, 1988; Holmstrom and Wilhelmsson, 1988; Horvath et al., 1988; Alexandersson and Hedenstierna, 1989; Malaka and Kodama, 1990; Wilhelmsson and Holmstrom, 1992). Formaldehyde exposures in the home and school environment have also been associated with irritation and pulmonary function effects in children (Wantke et al., 1996; Smedje et al., 1997; Garrett et al., 1999; Smedje and Norback, 2001a; 2001b; Delfino et al., 2003).

i. Respiratory Effects and Irritation – Acute Exposure

Formaldehyde vapor produces immediate local irritation in mucous membranes, including eyes, nose, and the upper respiratory tract (Arts et al., 2006). Formaldehyde exposures of 0.25-1.39 ppm (1 ppm = 1.24 mg/m<sup>3</sup>) evoked numerous complaints of upper respiratory tract and eye irritation among embalmers at different funeral homes (Kerfoot and Mooney, 1975). Anatomy class students exposed to an average of 1.1 ppm (standard deviation = 0.56 ppm) for 2 hours per week over 14 weeks experienced eye, nose and throat irritation (Kriebel et al., 2001). Exposure to low or moderate levels of formaldehyde (<1-3 ppm) can result in eye and upper respiratory tract irritation, headache, and rhinitis (inflammation of the mucous membrane of the nose) (Weber-Tschopp et al., 1977; Kulle et al., 1987). This has been observed in occupants of houses insulated with urea-formaldehyde foam insulation (UFFI), residents of mobile homes, and employees of mobile day-care centers (Olsen and Dossing, 1982; Ritchie and Lehnen, 1987), and noted in occupational settings.

Most people cannot tolerate exposures to more than 5 ppm formaldehyde in air, and above 10-20 ppm symptoms become severe and shortness of breath occurs. For example, 13.9 ppm formaldehyde for 30 minutes caused considerable nasal and eye irritation and continued mild lacrimation (abnormal or excessive secretion of tears) in human volunteer subjects (Sim and Pattle, 1957).

High concentrations of formaldehyde may result in severe mucous membrane irritation, burning, and lacrimation, nasal obstruction, choking, labored breathing, and chest tightness (Porter, 1975; Solomons and Cochrane, 1984a). Inhalation exposures to high concentrations can cause significant inflammation of the lower respiratory tract, resulting in swelling of the throat, inflammation of the windpipe and bronchi, narrowing of the bronchi, inflammation of the lungs, and accumulation of fluid in the lungs. Pulmonary injury may continue to worsen for 12 hours or more after exposure.

Rhinitis and a wide range of asthma-like conditions can result from exposure to formaldehyde. Even fairly low concentrations of formaldehyde can produce rapid onset of nose and throat irritation, causing coughing, chest pain, shortness of breath, and wheezing. Persons who are sensitized to formaldehyde may also

experience headaches, minor eye and airway irritation, asthma, and dermatitis (inflammation of the skin), even at very low doses. Previously sensitized individuals can develop severe constriction of the bronchi at very low concentrations (e.g. 0.3 ppm). Bronchial constriction may begin immediately or can be delayed for 3 to 4 hours; effects may worsen for up to 20 hours after exposure and can persist for several days. Lower respiratory effects can include bronchitis (acute or chronic inflammation of the bronchial tubes), pulmonary edema (abnormal accumulation of fluid in the lungs), or pneumonia.

Exposure to 3 ppm formaldehyde for 1 hour in a controlled exposure study resulted in clinically significant reductions in respiratory rates in both asthmatic and normal subjects (Green et al., 1987). Exposure to formaldehyde adversely affects pulmonary functioning with decreases in peak expiratory flow (PEF) of 1% per ppm of formaldehyde (Kriebel et al., 2001). The effects of formaldehyde on asthmatics may be dependent on previous, repeated exposure in worker studies (Burge et al., 1985). Some studies indicate that asthmatics may not be more sensitive than non-asthmatics to the respiratory effects of formaldehyde unless specifically sensitized to formaldehyde, such as occurs in occupational settings. However, as noted below, chronic low level exposure may be associated with asthma development in children.

Formaldehyde provocation of human subjects occupationally exposed to formaldehyde at concentrations of 1.5 to 20.6 ppm and suffering from asthma-like symptoms such as wheezing, shortness of breath, or rhinitis, also resulted in pulmonary function decrements consistent with immediate and/or delayed bronchoconstriction (constriction of the bronchial air passages) (Hendrick and Lane, 1977; Wallenstein et al., 1978; Burge et al., 1985; Nordman et al., 1985). Workers exposed to low concentrations may develop severe prolonged asthma attacks after prior exposure; this suggests that they may have become sensitized (Feinman, 1988). Histology technicians exposed to formaldehyde volatilized from formalin at concentrations of 0.2 to 1.9 ppm were shown to have reduced pulmonary function, compared with controls (Kilburn et al., 1989). Furthermore, 3 out of 15 occupationally exposed workers challenged with formaldehyde vapors at concentrations from 1.5 ppm to 20.6 ppm for a brief duration, exhibited late asthmatic reactions (Burge et al., 1985). Six other subjects had immediate asthmatic reactions likely due to irritant effects. Asthmatic responses were also observed in 12 occupationally-exposed workers challenged with 1.67 ppm formaldehyde (Nordman et al., 1985).

## ii. Chronic Human Exposure

Formaldehyde exposure primarily affects the mucous membranes of the upper airways and eyes. Chronically exposed populations that have been studied include embalmers, residents in houses insulated with urea-formaldehyde foam, anatomy class students, histology technicians, wood and pulp mill workers, and asthmatics. The literature describing these effects is briefly summarized below.

## iii. Exposure to Residents

Occupants of houses insulated with urea formaldehyde foam insulation (UFFI) (1726 subjects) were compared with control subjects (720 subjects) for subjective measures of irritation, pulmonary function (FVC, FEV<sub>1</sub>, FEF<sub>25-75</sub>, FEF<sub>50</sub>), nasal airway resistance, odor threshold for pyridine, nasal cytology, and hypersensitivity skin-patch testing (Broder et al., 1988). The mean length of time of exposure to UFFI was 4.6 years. A significant increase in symptoms of eye, nose and throat irritation was observed in subjects from UFFI homes (average exposure 0.043 ppm), compared with controls (average exposure 0.035 ppm). No other differences from control measurements were observed (Broder et al., 1988).

Doctor-diagnosed asthma and chronic bronchitis have been found to be more prevalent in houses with elevated formaldehyde (Krzyzanowski et al., 1990). Compared with children exposed in their homes to less than 8 ppb, children in homes with formaldehyde levels greater than 49 ppb had a 39% higher risk of asthma after adjusting for common asthma risk factors (Rumchev et al., 2002). Exposure concentrations as low as 0.09 ppm formaldehyde exacerbated chronic respiratory and allergy problems in residents living in mobile homes (Liu et al., 1991).

Ritchie and Lehnen (1987) reported a dose-dependent increase in health complaints (eye and throat irritation, and headaches) in 2000 residents living in 397 mobile and 494 conventional homes, that was demonstrated by logistic regression. Complaints of symptoms of irritation were noted at concentrations of 0.1 ppm formaldehyde or above. Similarly, Liu et al. (1991) found that exposure to 0.09 ppm (0.135 mg/m<sup>3</sup>) formaldehyde exacerbated chronic respiratory and allergy problems in residents living in mobile homes.

Employees of mobile day-care centers (66 subjects) reported increased incidence of eye, nose and throat irritation, unnatural thirst, headaches, abnormal tiredness, menstrual disorders, and increased use of analgesics as compared to control workers (Olsen and Dossing, 1982). The mean formaldehyde concentration in these mobile units was 0.29 ppm (0.43 mg/m<sup>3</sup>) (range = 0.24 - 0.55 mg/m<sup>3</sup>). The exposed workers were exposed in these units a minimum of 3 months. A control group of 26 subjects in different institutions was exposed to a mean concentration of 0.05 ppm (0.08 mg/m<sup>3</sup>) formaldehyde.

#### iv. Occupational Exposures

Kerfoot and Mooney (1975) reported that estimated formaldehyde exposures of 0.25-1.39 ppm evoked numerous complaints of upper respiratory tract and eye irritation among seven embalmers at six different funeral homes. Three of the seven embalmers in this study reportedly had asthma. Levine et al. (1984) examined the death certificates of 1477 Ontario undertakers. Exposure measurements taken from a group of West Virginia embalmers were used as exposure estimates for the embalming process, ranging from 0.3-0.9 ppm (average 1-hour exposure) and 0.4-2.1 ppm (peak 30-minute exposure). Mortality due to non-malignant diseases was significantly elevated due to a two-fold excess of deaths related to the digestive system. The authors suggest increased alcoholism could have contributed to this increase.

An increase in severity of nasal epithelial histological lesions, including loss of cilia and goblet cell hyperplasia (11%), squamous metaplasia (78%), and mild dysplasia (8%), was observed in 75 wood products workers exposed to between 0.1 and 1.1 mg/m<sup>3</sup> (0.08-0.89 ppm) formaldehyde for a mean duration of 10.5 years (range = 1 - 39 years), compared to an equal number of control subjects (Edling et al., 1988). Only three exposed men had normal mucosa. A high frequency of symptoms relating to the eyes and upper airways was reported in exposed workers. Nasal symptoms included mostly a runny nose and crusting. The histological grading showed a significantly higher score for nasal lesions when compared with the referents (2.9 versus 1.8). Exposed smokers had a higher, but non-significant, score than ex-smokers and non-smokers. When relating the histological score to duration of exposure, the mean histological score was about the same regardless of years of employment. In addition, no difference in the histological scores was found between workers exposed only to formaldehyde and those exposed to formaldehyde and wood dust.

Chronic occupational exposure to formaldehyde concentrations estimated to be 0.025 ppm for greater than six years resulted in complaints by 22 exposed workers of respiratory, gastrointestinal, musculoskeletal, and cardiovascular problems, a higher incidence of abnormal chest x-rays, and elevated formic acid excretion in the urine (Srivastava et al., 1992). A control group of 27 workers unexposed to formaldehyde was used for comparison. A significantly higher incidence of abnormal chest x-rays was observed in formaldehyde-exposed workers compared with controls.

Alexandersson et al. (1982) compared the irritant symptoms and pulmonary function of 47 carpentry workers exposed to a mean concentration of formaldehyde of 0.36 ppm (range = 0.04 - 1.25 ppm) with 20 unexposed controls. The average length of employment for the exposed workers was 5.9 years. Symptoms of eye and throat irritation as well as airway obstruction were more common in exposed workers. In addition, a significant reduction in FEV<sub>1</sub>,

FEV<sub>1</sub>/FVC, and MMF was observed in exposed workers, as compared with controls.

Alexandersson and colleagues studied workers (38 total) exposed for a mean duration of 7.8 years to 0.11 - 2.12 ppm (mean = 0.33 ppm) formaldehyde for symptomatology, lung function, and total IgG and IgE levels in the serum (Alexandersson and Hedenstierna, 1989). The control group consisted of 18 unexposed individuals. Significant decrements in pulmonary function (FVC and FEV<sub>1</sub>) were observed, compared with the controls. Eye, nose, and throat irritation was also reported more frequently by the exposed group, compared with the control group. No correlation was found between duration of exposure, or formaldehyde concentration, and the presence of IgE and IgG antibodies.

Chemical plant workers (70 subjects) exposed to a mean of 0.17 ppm (0.26 mg/m<sup>3</sup>) formaldehyde for an unspecified duration were compared with 36 control workers not exposed to formaldehyde (Holmstrom and Wilhelmsson, 1988). The exposed subjects exhibited a higher frequency of eye, nose, and deep airway discomfort. In addition, the exposed subjects had diminished olfactory ability, delayed mucociliary clearance, and decreased FVC.

Horvath et al. (1988) compared subjective irritation and pulmonary function in 109 workers exposed to formaldehyde with similar measures in a control group of 254 subjects. The formaldehyde concentrations for the exposed and control groups were 0.69 ppm (1.04 mg/m<sup>3</sup>) and 0.05 ppm (0.08 mg/m<sup>3</sup>), respectively. Mean formaldehyde concentration in the pre-shift testing facility and the state (Wisconsin) ambient outdoor - formaldehyde level were both 0.04 ppm (0.06 mg/m<sup>3</sup>). Duration of formaldehyde exposure was not stated. Subjects were evaluated pre- and post work-shift and compared with control subjects. Significant differences in symptoms of irritation, FEV<sub>1</sub>, FEV<sub>1</sub>/FVC ratio, FEF<sub>50</sub>, FEF<sub>25</sub>, and FEF<sub>75</sub> were found when comparing exposed subjects' pre- and post work-shift values. However, the pre-workshift values were not different from controls.

Significant increase in symptoms of irritation were reported for 66 workers exposed for 1 - 36 years (mean = 10 years) to a mean concentration of 0.17 ppm (0.26 mg/m<sup>3</sup>) formaldehyde (Wilhelmsson and Holmstrom, 1992). Controls (36 subjects) consisted of office workers in a government office and were exposed to a mean concentration of 0.06 ppm (0.09 mg/m<sup>3</sup>) formaldehyde. The significant increase in symptoms of irritation in exposed workers did not correlate with total serum IgE antibody levels. However, two exposed workers, who complained of nasal discomfort, had elevated IgE levels.

#### v. Immunological Effects in Humans

The binding of formaldehyde to endogenous proteins creates haptens that can elicit an immune response. This underlies sensitization of formaldehyde exposed

individuals and may explain the induction of asthma in occupationally exposed individuals as well as the indications of increased asthma in children exposed at home. Chronic exposure to formaldehyde has been associated with immunological hypersensitivity as measured by elevated circulating IgG and IgE auto-antibodies to human serum albumin (Thrasher et al., 1987). In addition, a decrease in the proportion of T-cells was observed, indicating altered immunity. Thrasher et al. (1990) later found that long-term exposure to formaldehyde was associated with auto-antibodies, immune activation, and formaldehyde-albumin adducts in patients occupationally exposed, or residents of mobile homes and homes containing particleboard sub-flooring (Thrasher et al., 1990).

Gorski et al. 1992 evaluated the production of active oxygen species by neutrophils in 18 persons exposed to 0.5 mg/m<sup>3</sup> (0.3 ppm) formaldehyde for two hours (Gorski et al., 1992). All 13 subjects who had allergic contact dermatitis (tested positive to formaldehyde in skin patch) exhibited significantly higher chemiluminescence of granulocytes isolated from whole blood 30 minutes and 24 hours post-exposure than the individuals who were not formaldehyde sensitive. Thus, the immune cellular response of skin-sensitized individuals to an inhalation exposure to formaldehyde indicates increased production of active oxygen species, and demonstrates that inhalation exposures can elicit immune and inflammatory reactions in sensitized individuals.

#### vi. Reproductive and Developmental Effects in Humans

There are no conclusive data showing that formaldehyde is toxic to the reproductive system or to developing fetuses in humans. Epidemiological studies of occupationally exposed individuals showed no clear evidence of either maternal or paternal inhalation exposure to formaldehyde associated with increased risk of spontaneous abortion (Hemminki et al., 1985; Lindbohm et al., 1991; John et al., 1994; Taskinen et al., 1994).

In humans there are few data on the association of teratogenicity or adverse reproductive effects with formaldehyde exposure. Existing data do not suggest that formaldehyde, by inhalation or oral routes, produces significant teratogenic or reproductive effects (ATSDR, 1999).

#### vii. Infants and Children

There are a number of physiological and behavioral factors that influence response to toxicants and differ between children and adults (OEHHA, 2001). Pharmacokinetic differences between children and adults include factors that influence absorption, distribution, metabolism, and excretion of toxicants. In addition, infants and children may have qualitatively different responses due to different target tissue sensitivities during windows of susceptibility in the developmental process.

There is evidence that following acute exposure to formaldehyde, asthmatics and others previously sensitized to formaldehyde may be more likely to show asthma-like symptoms such as wheezing, shortness of breath, rhinitis, and/or decrements in pulmonary function consistent with immediate and/or delayed bronchoconstriction (Hendrick and Lane, 1977; Wallenstein et al., 1978; Burge et al., 1985; Nordman et al., 1985). Furthermore, some asthmatics may respond with significant reductions in lung function due to the irritant effects on asthma, sensitized or not. The potential association between formaldehyde exposure and asthma is of special concern for children because they have higher prevalence rates of asthma than adults, and their asthma episodes can be more severe due to their smaller airways, which may result in more hospitalizations of children, especially for the first four years of life (Mannino et al., 1998). In several studies, asthma symptoms in secondary school children were more common in schools with higher concentrations of formaldehyde (Harving et al., 1990; Smedje et al., 1997; Smedje and Norback, 2001b). In addition, the incidence of new asthma diagnosis was more common in children whose classrooms had higher concentrations of formaldehyde (Smedje and Norback, 2001a). Thus children, particularly asthmatic children, may be at greater risk from acute exposure to formaldehyde.

There are few chronic studies that compare the effects of formaldehyde on children versus adults. Among those that do, there is evidence that children are more susceptible to the adverse effects of chronic formaldehyde exposure. Krzyzanowski et al. (1990) assessed chronic pulmonary symptoms and function in 298 children (6-15 years of age) and 613 adults (> 15 years of age) in relation to measured formaldehyde levels in their homes (Krzyzanowski et al., 1990). Information on pulmonary symptoms and doctor-diagnosed asthma and chronic bronchitis was collected by questionnaire. Pulmonary function was assessed as peak expiratory flow rates (PEF) measured up to four times a day. The prevalence of chronic respiratory symptoms in children was not related to formaldehyde levels measured in tertiles (< 40, 41-60, > 60 ppb). However, doctor-diagnosed asthma and chronic bronchitis were more prevalent in houses with elevated formaldehyde ( $p$  for trend < 0.02). This effect was driven by the high disease prevalence observed in homes with kitchen formaldehyde levels >60 ppb, and was especially pronounced among children with concomitant exposure to environmental tobacco smoke. By comparison, in adults, while the prevalence rates of chronic cough and wheeze were somewhat higher in houses with higher formaldehyde, none of the respiratory symptoms or diseases was significantly related to formaldehyde levels (Krzyzanowski et al., 1990).

In a random effects model, Krzyzanowski et al. (1990) found that lung function (measured as peak expiratory flow (PEF) in children, but not adults, was significantly decreased by formaldehyde (coefficient for household mean formaldehyde  $\pm$  SE:  $-1.28 \pm 0.46$  vs  $0.09 \pm 0.27$ ) (Krzyzanowski et al., 1990). Measurements of PEF in the morning suggested that children with asthma were more severely affected than healthy children (coefficient  $\pm$  SE:  $1.45 \pm 0.53$  p

<0.05) vs  $0.09 \pm 0.15$  ( $p > 0.10$ )). The authors note no threshold was found for formaldehyde effects on ventilatory function in the children, and that a 10% decrease in PEF was associated with exposures as low as 30 ppb in non-asthmatic children with an even larger effect in asthmatic children at 30 ppb. Compared to children, the effects of formaldehyde on pulmonary function in adults were smaller, transient, limited to morning measurements, and generally most pronounced among smokers exposed to the higher levels of formaldehyde. These studies suggest that children may be more susceptible to the effects of chronic formaldehyde exposure on lung function than are adults.

Among studies of children only, a case-control study examined risk factors for asthma among young children (6 mo- 3 yr) (Rumchev et al., 2002). Cases included children with clinically-diagnosed asthma, and controls were children of the same age group without such a diagnosis. Formaldehyde levels were measured in the homes, once in summer and once in winter. Questionnaires were used to assess potential risk factors for asthma and collect parental reports of respiratory symptoms characteristic of asthma (cough, shortness of breath, wheeze, runny nose, trouble breathing, and hay fever in their children) (Rumchev et al., 2002). Formaldehyde levels were higher in the homes of children exhibiting asthma symptoms. Estimates of the relative risk for asthma (odds ratios) were adjusted for measured indoor air pollutants, relative humidity, temperature, atopy (hereditary allergy), family history of asthma, age, gender, socioeconomic status, pets, smoke exposure, air conditioning, and gas appliances. Compared with children exposed to < 8 ppb, children in homes with formaldehyde levels > 49 ppb had a 39% higher risk of asthma ( $p < 0.05$ ) after adjusting for common asthma risk factors (Rumchev et al., 2002).

Franklin et al. (2000) measured exhaled nitric oxide levels in 224 children 6-13 years of age as an indicator of inflammation of the lower airways following chronic low-level formaldehyde exposure in the home (Kitaeva et al., 1990; Franklin et al., 2000). While there was no effect of formaldehyde on lung function measured by spirometry, eNO was significantly higher in children from homes with average formaldehyde levels  $\geq 50$  ppb compared with those from homes with levels  $\leq 50$  ppb (15.5 ppb eNO vs 8.7;  $p = 0.02$ ) (Franklin et al., 2000).

Garrett et al. (1999) examined the association between formaldehyde levels at home (median  $15.8 \mu\text{g}/\text{m}^3$ ; maximum  $139 \mu\text{g}/\text{m}^3$ ) and atopy and allergic sensitization in 148 children, 7-14 years of age (Garrett et al., 1999). The risk of atopy increased by 40% with each  $10 \mu\text{g}/\text{m}^3$  increase in formaldehyde measured in the bedroom. Two measures of allergic sensitization to 12 common environmental allergens, the number of positive skin prick tests and maximum wheal size, both showed linear associations with increasing maximum formaldehyde exposure levels. After adjusting for parental asthma and allergy, there was no evidence of an association between asthma in the children and formaldehyde levels. However, these data do suggest that formaldehyde levels

commonly found in homes can enhance sensitization of children to common aeroallergens (Garrett et al., 1999).

Of the numerous, primarily occupational, studies in adults, the NOAEL and LOAEL are  $32 \mu\text{g}/\text{m}^3$  (26 ppb) and  $92 \mu\text{g}/\text{m}^3$  (75 ppb), respectively, after adjustment for exposure continuity to formaldehyde. These data are based on nasal and eye irritation observed in Wilhelmsson and Holstrom (1992), and histological lesions in the nasal cavity documented in Edling et al. (1988). However, studies in children, including the Krzyzanowski study above, indicate adverse health impacts in children at concentrations as low as 30 ppb.

Wantke et al. (1996) reported that formaldehyde-specific IgE and respiratory symptoms were reduced when children transferred from schools with formaldehyde concentrations of 43 to 75 ppb to schools with concentrations of 23 to 29 ppb (Wantke et al., 1996). However, the prevalence of IgE sensitization in Japanese school children was not significant whether or not they had asthma (Doi et al., 2003). Formaldehyde in indoor air was significantly related to bacterial-specific IgG among Hungarian asthmatic children (Erdei et al., 2003). While these human studies are not entirely consistent with each other, and there is potential for confounding in each, nevertheless, taken together, they suggest that children are more sensitive to formaldehyde toxicity than adults. Findings by Delfino et al. (2003) also support the view that toxic air contaminants, such as formaldehyde, in communities in proximity to major emission sources, including both industrial and traffic sources, have adverse effects on asthma in children (Delfino et al., 2003). The odds ratio for more severe asthma symptoms per interquartile range (3.16 ppb formaldehyde) were 1.37 (95% CI 1.04-1.80).

## b. Health Effects in Experimental Animals

### i. Acute Animal Studies

Studies of the acute effects of formaldehyde exposure in experimental animals with exposure durations ranging from 30 minutes to 10 hours resulted in irritation, decrements in respiratory functioning, respiratory distress, and lethality. In rats exposed to formaldehyde vapor 500-1,400 ppm (1 ppm =  $1.24 \text{ mg}/\text{m}^3$ ) for 30 minutes, the lethal concentration to 50% of the exposure group ( $\text{LC}_{50}$ ) was 800 ppm (Skog, 1950). The first deaths did not occur until 6 hours after cessation of exposure; respiratory difficulty lasted several days after exposure; and several died after 15 days of bronchitis and diffuse bronchopneumonia. Three weeks following exposure, histological examinations of the surviving animals revealed bronchitis, pulmonary micro-hemorrhages, and edema. The report stated that formaldehyde exposure resulted in delayed lethality (Skog, 1950).

Exposure of mice to high concentrations of formaldehyde (726 ppm) for 2 hours, resulted in deaths from massive pulmonary hemorrhage and edema, but 2-hr exposure to 113 ppm did not produce signs of "substantial distress" (Horton et

al., 1963). Alarie (1981) determined the 10-minute LC<sub>50</sub> for formaldehyde in mice to be 2,162 ppm (95% CI, 1,687-2,770 ppm) (Alarie, 1981). In an acute lethality study, 125 or 250 ppm formaldehyde for 4 hours resulted in deaths of albino rats (Carpenter et al., 1949). In another lethality study, the LC<sub>50</sub> in rats and mice for a 4-hour formaldehyde exposure was 474 ppm and 407 ppm, respectively (Nagorny et al., 1979). A multi-species study showed that a 10-hr exposure to 15.4 ppm formaldehyde vapor killed 3 of 5 rabbits, 8 of 20 guinea pigs, and 17 of 50 mice (Salem and Cullumbine, 1960).

Amdur notes that exposure of guinea pigs to formaldehyde for one hour increases resistance and decreases compliance relative to the control level at 0.31 ppm and above ( $p < 0.05$ ) (Amdur, 1960).

Swiecechowski et al. exposed guinea pigs to 0.86, 3.4, 9.4, or 31.1 ppm formaldehyde for 2 hours, or to 0.11, 0.31, 0.59, or 1.05 ppm formaldehyde for 8 hours (Swiecichowski et al., 1993). An 8-hour exposure to  $\geq 0.3$  ppm formaldehyde was sufficient to produce a significant increase in airway reactivity. Similar effects occurred after  $> 9$  ppm ( $> 11$  mg/m<sup>3</sup>) formaldehyde for the 2-hour exposure group. Formaldehyde exposure also heightened airway smooth muscle responsiveness to acetylcholine (or carbachol) *ex vivo*.

Riedel et al. studied the influence of formaldehyde exposure on allergic sensitization in the guinea pig (Riedel et al., 1996). Exposure to formaldehyde concentrations (0.13 and 0.25 ppm) over 5 consecutive days, followed by sensitization to ovalbumin (OA) resulted in enhanced sensitization relative to filtered air controls ( $P < 0.01$ ). Furthermore, compressed air measurements of specific bronchial provocation were significantly higher in the 0.25 ppm formaldehyde group than in controls ( $p < 0.01$ ), indicating increased bronchial obstruction. Histological examination found edema of the bronchial mucosa, but there was no sign of inflammation of the lower airways in formaldehyde-exposed guinea pigs. The investigators concluded that short-term exposure to a low concentration of formaldehyde (0.25 ppm) can significantly enhance sensitization to inhaled allergens in the guinea pig.

Mice exposed to 0.2 to 13 ppm formaldehyde showed a concentration-dependent decrease in respiratory rate, which was attributable to sensory irritation at 0.3 to 4.0 ppm, and, above 4 ppm, also to bronchoconstriction (Nielsen et al., 1999).

Taken together, these acute animal studies show that formaldehyde is a respiratory irritant at low exposures, and can aggravate asthma-like conditions.

## ii. Reproductive and Developmental Toxicity

A developmental toxicity study on formaldehyde was conducted on pregnant rats (25 per group) that were exposed to 0, 2, 5, or 10 ppm formaldehyde for 6 hours/day, during days 6-15 of gestation (Martin, 1990). Although exposure to

10 ppm formaldehyde resulted in reduced food consumption and body weight gain in the maternal rats, no effects on the number, viability or normal development of the fetuses were seen. In addition, pregnant rats (25 per group) were exposed to 0, 5, 10, 20, or 40 ppm formaldehyde from days 6 - 20 of gestation (Saillenfait et al., 1989). Maternal weight gain and fetal weight were significantly reduced in the 40 ppm exposure group. No significant fetotoxicity or teratogenic defects were observed at formaldehyde levels that were not also maternally toxic (Saillenfait et al., 1989).

Evidence of embryotoxicity was reported in embryos of rats that had been exposed to formaldehyde by inhalation 4 h/d, 5 d/wk for 4 months (Kitaeva et al., 1990). At 1.5 mg/m<sup>3</sup>, but not at 0.5 mg/m<sup>3</sup>, there was a significant increase in the proportion of degenerate embryos. By comparison, the bone marrow cells of the mothers appeared to be more sensitive to formaldehyde as shown by significant increases in the numbers of cells with aberrations, and the numbers of chromosomes with aberrations and aneuploidy at both dose levels (Kitaeva et al., 1990).

### iii. Sub-chronic Animal Studies

Sub-chronic studies in rats and mice exposed to formaldehyde have shown histopathological changes (tissue changes characteristic of disease) in the nasal respiratory epithelium and nasal lesions in a dose-dependent manner (Monteiro-Riviere and Popp, 1986). In the nasal respiratory epithelium of adult male rats with exposure to 0.5 or 2 ppm formaldehyde, effects were limited to altered cilia (minute short hair-like processes, capable of lashing movement) with occasional wing-like projections on the ends of the ciliary shafts. Loss of microvilli (microscopic projections of tissues, cells, or cell organelles) in ciliated cells was noted at all exposure concentrations (Monteiro-Riviere and Popp, 1986). Intermittent exposures (8 hours/day, 5 days/week) of rats to 4 ppm formaldehyde for 13 weeks resulted in significant histological changes in the nasal septum and turbinates; however, 2 ppm did not produce significant lesions (Wilmer et al., 1989). This study revealed the concentration-dependent nature of the nasal lesions caused by formaldehyde exposure.

When male and female Wistar rats were exposed to 0.3 to 3 ppm formaldehyde vapor (6 hours/day, 5 days/week) for 13 weeks, histopathological nasal changes varying from epithelial disarrangement to epithelial hyperplasia (abnormal or unusual increase in epithelial cells composing a tissue) and squamous metaplasia (abnormal replacement of cells of one type by cells of another) were found in the 3 ppm group, and were restricted to a small area of the anterior respiratory epithelium (Zwart et al., 1988). In another subchronic study, rats were exposed to formaldehyde 0 to 20 ppm (6 hours/day, 5 days/week) for 13 weeks (Woutersen et al., 1989). Rats exposed to 20 ppm displayed retarded growth, yellowing of the fur, and significant histological lesions in the respiratory epithelium. Exposure to 10 ppm did not affect growth, but resulted in significant

histological lesions in the respiratory tract. No significant adverse effects were seen at the 1.0 ppm exposure level (Woutersen et al., 1989).

Mice exposed subchronically to 0 to 40 ppm formaldehyde (6 hours/day, 5 days/week) for 13 weeks had histological lesions in the upper respiratory epithelium ( $\geq 10$  ppm) and exposure to 40 ppm was lethal (Maronpot et al., 1986).

#### iv. Chronic Animal Studies

Nasal lesions of the respiratory and olfactory epithelium have been observed after chronic inhalation exposure of mice and rats to formaldehyde (Kerns et al., 1983; Rusch et al., 1983; Appelman et al., 1988; Woutersen et al., 1989; Kamata et al., 1997; Kimbell et al., 1997). Fischer-344 rats and B6C3F1 mice were exposed to 0 to 14.3 ppm formaldehyde vapor (6 hours/day, 5 days/week) for 24 months (Kerns et al., 1983). The exposure period was followed-up by 6 months of non-exposure with interim sacrifices conducted at 6, 12, 18, 24, 27, and 30 months. Both male and female rats in the 5.6 and 14.3 ppm groups demonstrated decreased body weights over the 2-year period. At the 6 month sacrifice, the rats exposed to 14.3 ppm formaldehyde had non-neoplastic lesions of epithelial dysplasia (abnormal growth or development) in the nasal septum and turbinates (Kerns et al., 1983). As the study progressed, epithelial dysplasia, squamous dysplasia, mucopurulent discharge (containing mucus and pus), and rhinitis increased in severity and distribution in all exposure groups (Kerns et al., 1983). In B6C3F1 mice, cumulative survival decreased in males from 6 months to the end of the study. Serous rhinitis was detected at 6 months in the 14.3 ppm group of mice. Metaplastic and dysplastic changes were noted at 18 months in most rats in the 14.3 ppm group and in a few mice in the 5.6 ppm exposure group. By 24-months, the majority of mice in the 14.3 ppm group had metaplastic and dysplastic changes associated with serous rhinitis, in contrast to a few mice in the 5.6 ppm group and a few in the 2 ppm group (Kerns et al., 1983).

At a similar dose of 10 ppm, compound-related nasal lesions of the respiratory and olfactory epithelium in male Wistar rats exposed 6 hours/day, 5 days/week to 0 to 10 ppm formaldehyde vapor for 28 months were observed (Woutersen et al., 1989). In the respiratory epithelium, the lesions consisted of rhinitis, squamous metaplasia and basal cell/pseudoepithelial hyperplasia. In the olfactory region, the lesions included epithelial degeneration and rhinitis. In a parallel study, male Wistar rats were exposed to 0 to 10 ppm formaldehyde for 3 months followed by a 25-month observation period. As with the previous studies, compound-related histopathological changes were found in the noses of the 10 ppm group and were comprised of increased incidences of squamous metaplasia of the respiratory epithelium and rhinitis (Woutersen et al., 1989).

Similar results were observed when male F-344 rats were exposed to formaldehyde vapor at 0 to 15 ppm (6 hours/day, 5 days/week) for up to 28

weeks (Kamata et al., 1997). Animals from each group were randomly selected at the end of 12, 18, and 24 months, and surviving animals at 28 months were sacrificed for full pathological evaluation. Behavioral effects related to sensory irritation were evident in the 15 ppm group. Abnormal histopathological findings were confined to the nasal cavity. Inflammatory cell infiltration, erosion or edema of the nasal cavity was evident in all groups, including controls. Significantly increased incidence of non-proliferative (squamous cell metaplasia without epithelial cell hyperplasia) and proliferative lesions (epithelial cell hyperplasia with squamous cell metaplasia) were observed in the nasal cavities beginning at 2 ppm. In the 0.3 ppm group, a non-significant increase in proliferative nasal lesions was observed in rats that were either sacrificed or died following the 18<sup>th</sup> month of exposure. Note that respiratory tract lesions also occur in occupationally exposed workers at lower formaldehyde concentrations.

Also using male F-344 rats exposed to 0 to 15 ppm formaldehyde (6 hours/day, 5 days/week) for up to 6 months, squamous metaplasia was not observed in any regions of the nasal cavity in the control, 0.7, or 2 ppm groups (Kimbell et al., 1997). However, the extent and incidence of squamous metaplasia in the nasal cavity increased with increasing dose beginning at 6 ppm (Kimbell et al., 1997). In a different study, significant nasal lesions were found in rats exposed to 10 ppm formaldehyde (6 hours/day, 5 days/week) for 52 weeks, but exposure to 1.0 ppm or less for this period did not result in nasal histological lesions (Appelman et al., 1988). However, Apfelbach and Weiler determined that rats (5 exposed, 10 controls) exposed to 0.25 ppm (0.38 mg/m<sup>3</sup>) formaldehyde for 130 days lost the olfactory ability to detect ethyl acetate odor (Apfelbach and Weiler, 1991).

Groups of 6 male cynomolgus monkeys, 20 male or female rats, and 10 male or female hamsters were exposed to 0 to 3.0 ppm formaldehyde vapor (22 hours/day, 7 days/week) for 26 weeks (Rusch et al., 1983). There was no treatment-related mortality during the study. In monkeys, the most significant findings were hoarseness, congestion and squamous metaplasia of the nasal turbinates in 6/6 monkeys exposed to 2.95 ppm. There were no signs of toxicity in the lower exposure groups (0.19 and 0.98 ppm). In the rat, squamous metaplasia and basal cell hyperplasia of the nasal epithelia were significantly increased in rats exposed to 2.95 ppm. The same group exhibited decreased body weights and decreased liver weights. In contrast to monkeys and rats, hamsters did not show any signs of response to exposure, even at 2.95 ppm.

More than 90% of inhaled formaldehyde gas is absorbed in the upper respiratory tract of rats and monkeys (Conolly et al., 2002). In rats, it is absorbed in the nasal passages; in monkeys, it is also absorbed in the nasopharynx, trachea and proximal regions of the major bronchi. In mice exposed to high concentrations of formaldehyde, minute ventilation is decreased by 50% throughout exposure, resulting in a lower effective dose. This occurs only transiently in rats, as the minute ventilation is rapidly restored.

Acute or subacute exposure of rats to a concentration of 2 ppm appears to cause no detectable damage to the nasal epithelium and does not significantly increase rates of cell turnover. Cell turnover rates in rat nose during subchronic or chronic exposures to formaldehyde do not increase at 2 ppm, increase marginally at concentrations of 3 to 6 ppm and increase substantially at concentrations of 10-15 ppm. Therefore, concentration is more important than length of exposure in determining the cytotoxicity of formaldehyde (Conolly et al., 2002). In a different study rats were exposed for six months to 0, 0.5, 3, and 15 ppm formaldehyde, which resulted in significantly elevated total lung cytochrome P450 in all formaldehyde-exposed groups (Dallas et al., 1989). The degree of P450 induction was highest after 4 days exposure and decreased slightly over the course of the experiment.

c. Human Carcinogenicity

i. Genotoxicity

Formaldehyde is genotoxic (damaging to genetic material) to humans. Increased numbers of DNA-protein crosslinks have been found in peripheral blood lymphocytes of exposed workers (Shaham et al., 1997; Shaham et al., 2002; Shaham et al., 2003). Formaldehyde induces DNA-protein crosslinks, DNA single-strand breaks, chromosomal aberrations, sister chromatid exchanges and gene mutations in human cells *in vitro* (Grafstrom et al., 1984; U.S.EPA, 1987; Shaham et al., 1996; IARC, 2004a; 2004b).

ii. Nasopharyngeal Cancer

Many studies in the epidemiological literature support a link between formaldehyde and elevated risk of cancers of the upper respiratory tract in workers and in the general population. According to the International Agency for the Research on Cancer (IARC), nasopharyngeal cancer mortality was statistically significantly increased in a cohort study of United States industrial workers exposed to formaldehyde in comparison with the U.S. national population, with statistically significant exposure-response relationships for peak and cumulative exposure (IARC, 2004a; 2004b). The individual studies used as the basis of this conclusion are described in further detail below.

Among the industrial cohort studies, Stayner et al. (1988) reported a relative risk of 3.4 (90% CI: 1.2-7.9) for buccal cancer (Stayner et al., 1988), and Blair et al. (1986) reported a relative risk of 3.00 (90% CI: 1.30-5.92) for nasopharyngeal cancer (Blair et al., 1986). Among industrial proportional mortality studies, Liebling et al.(1984) reported a relative risk of 8.70 (90% CI: 1.50-27.33) for buccal/pharyngeal cancer (Liebling et al., 1984) and Stayner et al. (1985) reported a relative risk of 7.5 (90% CI: 2.0-19) for buccal cancer (Stayner et al., 1985). In all of these studies the elevated risk was statistically significant. The population-based case control studies reported statistically significant

relationships between formaldehyde exposure and upper respiratory cancers in three studies (Olsen and Dossing, 1982; Hayes et al., 1986; Vaughan et al., 2000), although these cancers can appear in any of several sites. Studies of embalmers, who used formaldehyde, have shown increased rates of nasopharyngeal cancer, brain cancer and leukemia. A significant incidence of nasopharyngeal cancer was found among workers in fiberboard plants and among book binders, both being subject to formaldehyde exposure (Malaker et al., 1990).

IARC (2004) has reviewed available cohort studies including those of embalmers, industrial workers, and British chemical workers (IARC, 2004a; 2004b). An excess of nasopharyngeal cancer was observed in a proportionate mortality analysis for the largest U.S. cohort of embalmers (Hayes et al., 1990) and in a Danish study of proportionate cancer incidence among workers at companies which used or manufactured formaldehyde (Hansen and Olsen, 1995).

In a more recent study, evidence of an exposure-response relationship with mortality from nasopharyngeal cancer was found in a large cohort of formaldehyde-exposed workers, but not for cancers of the pancreas, brain, lung, or prostate (Hauptmann et al., 2004).

The relation of nasopharyngeal cancer with exposure to formaldehyde has also been investigated in seven case control studies (Olsen et al., 1984; Vaughan et al., 1986a; 1986b; Roush et al., 1987; West et al., 1993; Armstrong et al., 2000; Vaughan et al., 2000; Hildesheim et al., 2001), five of which found elevations of risk for overall exposure to formaldehyde, or in higher exposure categories, including one in which the increase in risk was statistically significant, and three that found higher risks in subjects with the highest probability, level or duration of exposure. The Working Group considered it improbable that all of the positive findings for nasopharyngeal cancer that were reported from the epidemiological studies, and particularly from the large study of industrial workers in the USA, could be explained by bias or unrecognized confounding effects. The Working Group concluded that these studies provide "sufficient epidemiological evidence that formaldehyde causes nasopharyngeal cancer in humans" (IARC, 2004a; 2004b).

Blair et al. (1987) presented further analysis resulting in a significant association between nasopharyngeal cancer and simultaneous exposure to formaldehyde and to particulate, indicating that such exposure may be a risk factor (Blair et al., 1987).

Recent occupational studies have investigated the relationship of formaldehyde exposure to histological changes, some of which are potentially precancerous lesions, in the nasal mucosa. Holmstrom et al. (1989) found that workers exposed to well-defined levels of formaldehyde developed significant changes in

the middle turbinate, while those exposed to both formaldehyde and wood dust did not (Holmstrom et al., 1989). Boysen et al. (1990) found in nasal biopses that workers exposed to formaldehyde showed a significantly higher degree of metaplastic alterations (Boysen et al., 1990). Edling et al. (1988) found significant histological differences in the nasal mucosa of formaldehyde workers compared to unexposed workers, but found no histological differences between those exposed to formaldehyde and those exposed to formaldehyde and wood dust (Edling et al., 1988). Berke (1987) found no statistical relationship between exfoliated nasal cells in formaldehyde-exposed workers and control groups. Thus, these studies provide some indication of possible histological changes due to formaldehyde exposure in humans, consistent with results in animals.

### iii. Leukemia

Leukemia mortality, primarily of the myeloid-type, was increased in six of seven cohorts of embalmers, funeral-parlor workers, pathologists, and anatomists (Walrath and Fraumeni, 1983; Levine et al., 1984; Walrath and Fraumeni, 1984; Logue et al., 1986; Stroup et al., 1986; Hayes et al., 1990; Hall et al., 1991) as reviewed by IARC 2004a; IARC 2004b. Recent evidence indicates a greater incidence of leukemia in two cohorts of U.S. industrial workers and U.S. garment workers, but not in a third cohort of United Kingdom chemical workers. Therefore, IARC concluded that there is “strong but not sufficient evidence for a causal association between leukemia and occupational exposure to formaldehyde” (IARC, 2004a; 2004b).

Until recently, the findings for leukemia in studies of professional workers appeared to be contradicted by the lack of such findings among industrial workers. However, some evidence for an excess of leukemia has been reported in the recent updates of two of the three major cohort studies of industrial workers. A statistically significant exposure–response relationship was observed between peak exposures to formaldehyde and mortality from leukemia in the study of industrial workers in the USA (Blair et al., 1990; Hauptmann et al., 2003). A recent meta-analysis found that, overall the relative risk for leukemia in these workers was increased and did not vary significantly among studies (Collins and Lineker, 2004).

Mortality from leukemia was also found to be in excess in the recent update of the study of garment workers exposed to formaldehyde in the U.S. (Pinkerton et al., 2004). A small and statistically non-significant excess was observed for the entire cohort in comparison with rates from the general population. This excess was somewhat stronger for myeloid leukemia, which is consistent with the findings from the study of industrial workers in the U.S. and several of the studies of medical professionals and embalmers. In contrast, the updated study of industrial workers in the U.K. did not find excess mortality from leukemia (Coggon et al., 2003).

Linos et al. reported elevated rates of follicular non-Hodgkin's lymphoma and of acute myeloid leukemia among embalmers and funeral directors in a population-based case control (Linos et al., 1990). The excess was also stronger among workers with long duration of exposure and long follow-up, and who had been employed early in the study period when exposures to formaldehyde were believed to be the highest. This pattern of findings is generally consistent with what might be expected if, in fact, exposure to formaldehyde were causally associated with risk for leukemia.

The IARC Working Group concluded, "In summary, there is strong but not sufficient evidence for a causal association between leukemia and occupational exposure to formaldehyde." This conclusion, falling between sufficient and limited evidence, was based on a consistently increased risk in studies of embalmers, funeral parlor workers, pathologists, and anatomists and was present in two of the three most informative studies of industrial workers (IARC, 2004a; 2004b).

#### iv. Lung Cancer

The three largest - and therefore potentially most sensitive - industrial cohort studies reported an elevated rate of lung cancer. The largest study with 26,561 U.S. workers, reported a statistically elevated death rate due to lung cancer, equivalent to 35% above the national average (Blair et al., 1986). Several other studies reported elevated death rates due to lung cancer (Acheson et al., 1984a; 1984b; 1984c) in 7,680 British male workers, mostly young, and in 11,030 US workers, mostly female (Stayner et al., 1988). Some of the categories in the Acheson study showed statistically significant increases of lung cancer (Acheson et al., 1984a; 1984b). The Stayner (1988) study found lung cancer to be elevated 14% overall, which was not statistically significant, but the exposures were well below those of the other two studies.

In Blair et al. (1986), the investigators concluded that a causal relationship between formaldehyde exposure and lung cancer was unlikely because of a lack of dose gradient for those tumors. Sterling and Weinkam (1988; 1989) performed a reanalysis on the basis that Blair et al. (1986) failed to account for a "healthy-worker" effect in the original report. These corrected results showed that lung cancer was related to formaldehyde exposure in a dose-dependent manner which was statistically significant (Sterling and Weinkam, 1988; 1989).

Recent epidemiological studies contribute to the conclusions only marginally. Gerin et al.(1989) presented the results of a large case control study with 3,726 cancer patients (Gerin et al., 1989). The odds ratio for the highest exposure group with adenocarcinoma of the lung was nearly significant at the 95% confidence level, and there was an apparent trend of incidence of this cancer with exposure. Bertazzi et al. (1989) presented an extension of a previous study (Bertazzi et al., 1986), that had detected elevated lung cancer among 1,332 workers in a resin B-289 manufacturing plant subject to formaldehyde exposure

(Bertazzi et al., 1989 as cited in IARC, 2004a; 2004b). In the extended study with more accurate estimates of exposure, the lung cancer rate was not elevated above expected for those exposed to formaldehyde (Bertazzi et al., 1989 as cited in IARC, 2004a; 2004b). Coggon et al. (2003) noted an increase in the risk of lung cancer, but not a significant association with mortality (Coggon et al., 2003). Based on the current data alone, a definitive relationship between formaldehyde exposure and lung cancer mortality could not be made by the IARC Working Group (IARC, 2004a; 2004b).

#### v. Sinonasal Cancer

The association between exposure to formaldehyde and risk for sinonasal cancer has been evaluated in six case–control studies with a primary focus on formaldehyde. Four of these studies also contributed to a pooled analysis that collated occupational data from 12 case–control investigations. After adjustment for known occupational confounders, this analysis showed an increased risk for adenocarcinoma in both men and women and also (although on the basis of only a small number of exposed cases) in the subset of subjects who were thought never to have been occupationally exposed to wood or leather dust. Moreover, there was a dose–response trend in relation to an index of cumulative exposure (Luce et al., 2002). One other case-control study (Olsen and Asnaes, 1986) and a proportionate incidence study (Hansen and Olsen, 1995) showed an increased risk of sinonasal cancer, particularly squamous cell carcinoma. Against these largely positive findings, the three most informative cohort studies of industrial and garment workers showed no excess of sinonasal cancer (Coggon et al., 2003; Hauptmann et al., 2004; Pinkerton et al., 2004).

The IARC Working Group noted that most of the epidemiological studies did not distinguish tumors as originating in the nose or sinuses, thus an increased risk of nasal cancer would be diluted if there were no corresponding effect on the sinuses. In the case-control studies, the Working Group also noted the potential for confounding by wood dust exposure, which is associated with nasopharyngeal adenocarcinoma. The Working Group concluded that there is limited evidence that formaldehyde causes sinonasal cancer in humans (IARC, 2004a; 2004b).

#### vi. Cancer at Other Sites

A number of studies have found associations between exposure to formaldehyde and cancer at other sites, including the oral cavity, oro- and hypopharynx, pancreas, larynx, lung and brain. However, the IARC 2004 Working Group considered that the overall balance of epidemiological evidence did not support a causal role for formaldehyde in relation to these other cancers (IARC, 2004a, IARC 2004b).

d. Animal Carcinogenicity

i. Genotoxicity

Formaldehyde is comprehensively genotoxic in a variety of experimental systems, ranging from bacteria to rodents, *in vivo*. Administration of formaldehyde in the diet to *Drosophila melanogaster* induced lethal and visible mutations, deficiencies, duplications, inversions, translocations and crossing-over in spermatogonia (Auerbach et al., 1977; Swenberg et al., 1983).

In rodent cells *in vitro*, formaldehyde induced cell transformation, chromosomal aberrations, sister chromatid exchange, DNA strand breaks, DNA-protein crosslinks and gene mutation (Cosma et al., 1988; Casanova et al., 1994; Merk and Speit, 1998; Speit and Merk, 2002). Inhalation of formaldehyde leads to the formation of DNA-protein cross-links in the nasal respiratory mucosa of rats and monkeys (Conaway et al., 1996). The formation of DNA-protein cross-links is a sublinear function of the formaldehyde concentration in inhaled air from 0.69 to 15 ppm, and the yield of DNA-protein cross-links at a given inhaled concentration is approximately an order of magnitude lower in monkeys than in rats. About 50% of formaldehyde-induced tumors in the nasal mucosa of rats have a point mutation in the *p53* tumor suppressor gene.

ii. Nasopharyngeal Cancer

In experimental animals, several studies have shown that inhalation exposure induces squamous cell carcinomas of the nasal cavities in rats (Albert et al., 1982; Kerns et al., 1983; Sellakumar et al., 1985; Morgan et al., 1986; Feron et al., 1988; Woutersen et al., 1989; Monticello et al., 1996; Kamata et al., 1997), although single studies in mice (Kerns et al., 1983) and hamsters (Dalbey, 1982) showed no carcinogenic effects. Several studies in which formaldehyde was administered to rats by inhalation showed evidence of carcinogenicity, particularly induction of squamous-cell carcinomas of the nasal cavities, usually only at the highest exposure. A chronic exposure study that primarily investigated aspects of nasal tumor development, examined rat nasal cavities following exposure to 0 - 15 ppm of formaldehyde for 6 hours/day, 5 days/week for 24 months (Monticello et al., 1996). Nasal lesions developed at 6, 10, and 15 ppm. The two highest doses included epithelial hypertrophy and hyperplasia, squamous metaplasia, and a mixed inflammatory cell infiltrate, but the lesions of the 6 ppm group were minimal to absent and limited to focal squamous metaplasia in the anterior regions of the nasal cavity (Monticello et al., 1996).

A study sponsored by the Chemical Industry Institute for Toxicology (CIIT) has provided the most quantitatively useful evidence for the carcinogenicity of formaldehyde (Swenberg et al., 1980a; Swenberg et al., 1980b; Kerns et al., 1983). This study used 120 male and 120 female Fischer-344 rats in each dose group, including a clean air group. The adjusted tumor incidences (adjusted for

competing causes of death, including scheduled interim sacrifices) for squamous cell carcinomas in the nasal passages of males and females combined, when exposed to 0 to 14.3 ppm formaldehyde (6 hours/day, 5 days/week) for up to 24 months, were 0/156, 0/159, 2/153 and 94/140 for the highest dose group (14.3 ppm) (USEPA, 1987).

In an analogous study on mice, two mice in the high dose group (14.3 ppm) developed squamous cell carcinomas, a finding that was not statistically significant, but was thought to be biologically significant due to the absence of this tumor in control animals and due to concurrence with the rat studies. Kerns et al. (1983) also reported benign tumors, including polypoid adenomas and squamous cell papillomas (Kerns et al., 1983). Swenberg et al. (1980) described a number of additional lesions in the nasal turbinates of rats exposed to formaldehyde for 18 months, including rhinitis, epithelial dysplasia and hyperplasia, squamous hyperplasia, and cellular atypia that occurred in a dose-related manner (Swenberg et al., 1980a; Swenberg et al., 1980b). Other inhalation studies (Albert et al., 1982; Tobe et al., 1985) have also provided positive evidence for the carcinogenicity of formaldehyde.

### iii. Leukemia

The IARC Working Group concluded, “The current data indicate that both genotoxicity and cytotoxicity play important roles in the carcinogenesis of formaldehyde in nasal tissues.” On the other hand, with respect to the potential for formaldehyde to induce leukemia, the Working Group was not aware of any good rodent models for acute myeloid leukemia in humans (IARC, 2004a; IARC 2004b). Several possible mechanisms were considered, such as clastogenic damage to circulating stem cells. There is a single study reporting cytogenetic abnormalities in the bone marrow of rats inhaling formaldehyde (Kitaeva et al., 1990). The Working Group concluded, “Based on the data available at this time, it was not possible to identify a mechanism for the induction of myeloid leukemia in humans” (IARC 2004a; IARC 2004b).

### iv. Other Routes of Exposure

Four studies of formaldehyde administered to rats in drinking-water gave varying results: one showed an increased incidence of forestomach papillomas in male rats (Takahashi et al., 1986), a second showed an increased incidence of gastrointestinal leiomyosarcomas in female rats and in both sexes combined (Soffritti et al., 1989), a third showed increased incidences of total malignant tumors, lymphomas and leukemias, and testicular interstitial-cell adenomas in male rats (Soffritti et al., 2002), while a fourth did not show a carcinogenic effect (Til et al., 1989).

Recent investigations of chronic toxicity have shown formaldehyde administered orally for 24 months to be carcinogenic in Sprague-Dawley rats. Six exposure groups each of 50 male and 50 female Sprague-Dawley rats, with drinking water concentration of 8 ppm to 1210 ppm formaldehyde, reported increases in the percent of B-290 animals bearing leukemias and gastrointestinal neoplasias at the higher exposures. Til et al. (1989), using three exposure groups, of 70 male and 70 female Wistar rats each, with drinking water concentrations of 16 to 1532 ppm, reported numerous pathological changes at the highest exposure level, but no evidence of carcinogenicity at any level. Tobe et al. (1989), using three exposure groups, of 20 male and 20 female Wistar rats each, with drinking water concentrations of 161 to 4032 ppm, also reported pathological changes at the highest exposures level but no significant increases in the incidence of any tumor in these small treatment groups (Tobe et al., 1989). In a letter to the editor, Feron et al. (1990) questioned the conclusions and some methods of Soffritti et al. (1989) (Feron et al., 1990).

Other types of exposures have produced a spectrum of results. Watanabe et al. (1954) presented a brief preliminary report of experimentally inducing sarcomas by repeated injections of an aqueous solution of formaldehyde in rats (Watanabe et al., 1954 as cited in IARC (2004)). Muller et al. (1978) induced a preneoplastic lesion of the oral mucosa by repeated exposure to formalin solution in rabbits. (Muller et al., 1978). Homma et al. (1986) found that formalin solution repeatedly administered in transplanted rat bladders did not promote the formation of tumors (Homma et al., 1986). Takahashi et al. (1986) found that formalin solution in the diet promoted stomach tumors in Wistar rats (Takahashi et al., 1986). Iversen et al. (1988) found that topical skin application of formaldehyde solution in mice did not promote the formation of skin tumors (Iversen et al., 1988).

#### v. Co-carcinogenicity

Formaldehyde has shown co-carcinogenic effects by inhalation, ingestion, and dermal exposure to rodents (Dalbey, 1982; Takahashi et al., 1986; Iversen et al., 1988). In additional studies in mice, rats and hamsters, modification of the carcinogenicity of known carcinogens was tested by administration of formaldehyde in drinking-water, by application on the skin or by inhalation. Oral administration of formaldehyde concomitantly with *N*-nitrosodimethylamine to mice increased the incidence of tumors at various sites. Exposure of hamsters to formaldehyde by inhalation increased the multiplicity of tracheal tumors induced by subcutaneous injections of *N*-nitrosodiethylamine (Morgan et al., 1986). Skin application of formaldehyde concomitantly with 7,12-dimethylbenz[*a*]anthracene reduced the latency of skin tumors in mice (Homma et al., 1986). In rats, concomitant administration of formaldehyde and *N*-methyl-*N'*-nitro-*N*-nitrosoguanidine in the drinking-water increased the incidence of adenocarcinoma of the glandular stomach (Tobe et al., 1989).

vi. Overall IARC Conclusion

The IARC Working Group concluded that formaldehyde is *carcinogenic to humans (Group 1)*, on the basis of *sufficient evidence* in humans and *sufficient evidence* in experimental animals. Based on the information now available, this classification is higher than those of earlier IARC evaluations (IARC 1982, 1987, 1995)(IARC 2004a; IARC 2004b).

**C. Factors that Affect the Outcome of a Health Risk Assessment**

Estimates of the potential health effects of HCHO emissions from composite wood products could be affected by:

- HCHO concentrations in indoor microenvironments;
- Rate of decrease in product-specific HCHO emissions with time;
- Initial product-specific HCHO emission rates;
- Air exchange rates in indoor microenvironments;
- Product-specific HCHO compensation points;
- Number and total surface area of HCHO-emitting products; and
- Practices utilized, if any, to reduce indoor HCHO exposure.

Variations in the numerical value of these factors will have substantive impacts on estimates of potential cancer risk and extent of non-cancer effects. For example, maintaining high air exchange rates and using air filtration systems could greatly reduce indoor exposures in homes, schools, and workplaces.

**D. Summary of Potential Health Impacts**

In this chapter, the results of the total daily HCHO exposure analyses are presented. As Californians spend 90% or more of their day indoors (University of California, Berkeley, 1991a), total daily HCHO exposure is predominantly determined by indoor air quality. Based on the exposure analysis, significant reductions in lifetime cancer risk may be realized by reducing HCHO emissions from composite wood products used as building materials and to fabricate finished products, such as furniture.

To calculate total daily exposure to HCHO requires data on activity patterns (i.e., time spent in different microenvironments; Table VII-3) and typical HCHO concentrations ( $\mu\text{g}/\text{m}^3$ ) in the selected microenvironments (Table VII-1). A daily TWA was calculated for an average and elevated exposure for adults and children (i.e., four scenarios – current-average and current-elevated for children and adults).

Table VII-3. Age-group Specific and Average Child and Adult Activity Patterns<sup>1</sup>

Age	T <sub>ind</sub> (hr)	T <sub>out</sub> (hr)	T <sub>inv</sub> (hr)	T <sub>total</sub> (hr)
0-2	21.43	1.57	1.01	24.00
3-5	20.47	2.38	1.15	23.99
6-8	20.34	2.83	0.83	24.00
9-11	19.69	3.28	1.03	24.01
12-17	21.23	1.00	1.78	23.99
18-24	20.55	1.23	2.22	24.01
25-34	20.98	1.21	1.83	23.99
35-44	20.65	1.36	1.98	23.96
45-54	20.95	0.98	2.03	23.96
55-64	20.64	1.73	1.63	23.99
65 <sup>+</sup>	21.57	1.15	1.3	24.02
Child – Average	20.55	2.45	1.00	24.00
Adult – Average	20.82	1.47	1.71	24.00

<sup>(1)</sup> Sources: University of California, Berkeley, 1991a and 1991b. T<sub>ind</sub> = time spent indoors; T<sub>out</sub> = time spent outdoors, T<sub>inv</sub> = time spent in-vehicles, and T<sub>total</sub> = (T<sub>ind</sub> + T<sub>out</sub> + T<sub>inv</sub>). Averages for children and adults are the average from age 0-9 and 0-70 years, respectively.

Summary data in two technical reports were used to calculate the average time spent indoors, outdoors, or in a vehicle (University of California, Berkeley, 1991a; 1991b). For children from age 0-11, average time spent was calculated as the mean for boys and girls for age groups 0-2, 3-5, 6-8, and 9-11 (University of California, Berkeley, 1991b). Activity patterns for adolescents and adults were calculated as the mean for men and women for age groups 12-17, 18-24, 25-34, 35-44, 45-54, 55-64, and 65<sup>+</sup> (University of California, Berkeley, 1991a). Over a conceptual 70-year lifetime, the standard exposure duration for health risk assessments (OEHHA, 2003), T<sub>ind</sub> ranged from 19.69 to 21.57 hr/day, T<sub>out</sub> from 0.98 to 3.28 hr/day, and T<sub>inv</sub> from 0.83 to 2.22 hr/day (Table VII-3).

Using the data in Tables VII-1 and VII-3, estimates of total daily HCHO exposure (µg/m<sup>3</sup>-hr) and daily time-weighted average HCHO concentration (µg/m<sup>3</sup>) were calculated (Table VII-4). Although adults spend more time indoors or in-vehicles, there are only slight differences in exposure and daily TWA compared to children.

Table VII-4. Estimates of Total Formaldehyde (HCHO) Exposure and Daily Time-weighted Average (TWA) Formaldehyde Concentration <sup>1</sup>					
Environment	Time (hr)	----- HCHO ( $\mu\text{g}/\text{m}^3$ ) -----		Exposure ( $\mu\text{g}/\text{m}^3\text{-hr}$ )	
		Average	Elevated	Average	Elevated
Child: Total Exposure and Daily TWA					
Indoors	20.65	17.2	46.7	355	964
In-vehicle	1.25	9.6	12	12	15
Outdoors	2.10	3.7	15	8	32
Total	24	-----	-----	375	1,011
Daily TWA	-----	-----	-----	15.6	42.1
Adult: Total Exposure and Daily TWA					
Indoors	20.82	17.2	46.7	358	972
In-vehicle	1.71	9.6	12	16	21
Outdoors	1.47	3.7	15	6	22
Total	24	-----	-----	380	1,015
Daily TWA	-----	-----	-----	15.8	42.3
<p><sup>(1)</sup> Sources: Refer to Tables VII-1 and VII-3. "HCHO" = formaldehyde; "<math>\mu\text{g}/\text{m}^3</math>" = micrograms per cubic meter; "<math>\mu\text{g}/\text{m}^3\text{-hr}</math>" = <math>\mu\text{g}/\text{m}^3</math>-hour. Exposure was calculated by multiplying "time" by average or elevated HCHO concentration. Daily TWA was calculated by dividing "Exposure" by 24-hours.</p>					

### E. Multi-pathway Health Risk Assessment

To evaluate the potential health effects of a TAC all the routes by which an individual may be exposed to the TAC need to be identified. The pathways or routes of pollutant exposure may include inhalation, dermal exposure, and ingestion of soil particles and food. For purposes of this HRA and rulemaking, inhalation is the principal pathway of HCHO exposure (95% or more), with small amounts of uptake by dermal exposure from disinfectant use. Therefore, analysis of impacts is based on exposure via inhalation only.

### F. Statewide Emission and Risk Reduction Benefits

The proposed ATCM would reduce emissions of HCHO from HWPW, PB, and MDF by approximately 20% in Phase 1 and approximately 57% in Phase 2, resulting in an estimated annual statewide emissions reduction of 180 and 500 tons per year, respectively. Because these emissions would substantially reduce indoor HCHO exposures, where HCHO levels are highest and where people spend approximately 90% of their time, the reduction in potential excess cancer

cases in children is estimated to range from 3 to 9 after Phase 1, and 9 to 26 after Phase 2 (Table VII-5).

Table VII-5. Estimated Cancer Risk in Children and Adults After Implementation of the Phase 1 and Phase 2 Emission Standards <sup>1</sup>			
Childhood Exposure: 9-year Exposure to Formaldehyde (HCHO)			
Exposure Scenario	TWA HCHO (µg/m <sup>3</sup> )	Cancer Risk Per Million	Cancer Cases Reduced
Current-average	16	23	-----
• Post Phase 1	13	20	3
• Post Phase 2	9	14	9
Current-elevated	42	63	-----
• Post Phase 1	36	54	9
• Post Phase 2	25	37	26
Lifetime Exposure: 70-year Exposure to Formaldehyde (HCHO)			
Exposure Scenario	TWA HCHO (µg/m <sup>3</sup> )	Cancer Risk Per Million	Cancer Cases Reduced
Current-average	16	86	-----
• Post Phase 1	14	74	12
• Post Phase 2	9	51	35
Current-elevated	42	231	-----
• Post Phase 1	36	196	35
• Post Phase 2	25	134	97
<sup>(1)</sup> "TWA HCHO" = Daily time-weighted average HCHO concentration. Changes in Phase 1 and Phase 2 TWA HCHO levels were calculated based on 16% and 44% reductions in HCHO levels in a home (Appendix E). Cancer risk was calculated according to OEHHA (2005c).			

For adults, reductions in cancer risk, based on a 70-year lifetime exposure, would be reduced by 12 to 35, and 35 to 97, after Phase 1 and Phase 2, respectively (Table VII-5).

Non-cancer chronic inhalation impacts were calculated by dividing the daily TWA exposure concentrations by the chronic inhalation REL for HCHO (i.e., 3 µg/m<sup>3</sup> for eye irritation) to derive a hazard quotient (OEHHA, 2003). Thus the hazard quotient based on the current-average TWA exposure concentration (15.8 µg/m<sup>3</sup>) would be 5.3 -- after Phase 1 and Phase 2, the hazard quotient would decrease

to 4.5 and 3.1, respectively. As all of these values are greater than one, there is a probability of adverse eye irritation effects from HCHO at current- and future daily TWA exposure concentrations. The current average, post-Phase 1, and post-Phase 2 hazard quotients for children were 5.2, 4.4, and 3.1, respectively. For the current-elevated scenario, hazard quotients were approximately 2.7 times higher than for the current-average scenario in all time frames.

## **G. Potential Adverse Health Effects from Replacement Compounds**

It is anticipated that most manufacturers will achieve the required emission reductions by lowering the amount of HCHO used in the UF resin systems that they presently use. However, greater use of existing low-formaldehyde or formaldehyde-free adhesives may be considered (i.e., phenol-formaldehyde, melamine-formaldehyde and isocyanates) in selected products. One HWPW manufacturer began the exclusive use of a soy flour-based adhesive in 2006.

### **1. Methylene Diphenyl Isocyanate (CAS No. 101-68-8)**

Methylene diphenyl isocyanate (MDI) is used in existing wood adhesives (Forest Products Laboratory, 1999). In consideration of potential respiratory effects, the chronic REL for MDI is  $0.7 \mu\text{g}/\text{m}^3$  in California (OEHHA, 2000). Workplaces are the primary source of exposure to MDI, where it is handled by workers using respirators (Massachusetts Toxics Use Reduction Institute, Not Dated; NIOSH, 2005). The USEPA (Not Dated) reported that there is inadequate data to classify MDI as a human carcinogen, consistent with a not classifiable designation by IARC (Massachusetts Toxics Use Reduction Institute, Not Dated). The USEPA (Not Dated) also reported that there was only limited data regarding animal carcinogenicity. It should be noted that panels made with MDI, once reacted in the production facility, do not continue to emit as do the current UF resin products.

### **2. Melamine (CAS No. 108-78-1)**

Presently, melamine-HCHO resins are used in the manufacture of HWPW, and HCHO emissions from these products were found to be intermediate to those of products bonded with urea-formaldehyde (high) and phenol-formaldehyde (low) (CARB 2003 Survey, unpublished data). Toxicity to mammals is low – it is not irritating to skin or eyes (OECD, 1998). Although one study found that melamine exposure produced urinary bladder tumors in male rats, it has not been classified as a carcinogen by IARC.

### **3. Phenol (CAS No. 108-95-2)**

Phenol is a hazardous air pollutant that was identified as TAC under AB 2728 (CARB, 1993). To a limited extent, manufacturers may choose to utilize phenol-HCHO resin in place of urea-formaldehyde for selected applications. Wood

products made with phenol-formaldehyde resins have very low HCHO emissions, and are exempt from the U.S. Housing and Urban Development standards for building materials used in mobile home construction (PFS Research Foundation, 2001). Phenol is a common industrial chemical used in a variety of manufacturing processes and household products (CARB, 1997c). While phenol is a strong eye and respiratory irritant, there are limited data concerning its chronic health effects in humans resulting from inhalation or oral exposure. Moreover, due to a lack of data, phenol has not been classified as a carcinogen by either USEPA or IARC.

#### **4. Soy Flour**

A soy flour based resin is scheduled for use in the manufacture of HWPW by Columbia Forest Products beginning in 2006 (McIsaac, 2005). Soy flour is a high protein powder generally made from dehulled, heat-processed soybeans or soybean flakes (Wikipedia Contributors, 2007). Soy flour is already being used in preparation and manufacture of a number of food products sold throughout the world, and its use as a wood adhesive is not expected to cause adverse non-cancer or cancer health effects.

#### **H. Workplace Exposure**

Formaldehyde is a TAC (CARB, 1992) that is classified as a known human carcinogen by IARC, and is an irritant to the eyes and the respiratory system. At concentrations ranging from 0.5 to 1.0 ppm, most individuals will experience eye, nose, and/or throat irritation. At concentrations greater than 1.0 ppm, HCHO causes extreme discomfort (OEHHA, 1999). Various workplace standards have been developed in consideration of these findings:

- U.S. Department of Labor's Occupational Safety & Health Administration (OSHA) adopted "Permissible Exposure Limits" (PEL) in 1992 of 0.75-ppm for an 8-hr workday, and a 2-ppm Short-term Exposure Limit (STEL) (Formaldehyde Council Inc., 2005);
- Australia "Worksafe Standards" are 1.0 ppm "time-weighted average" (TWA) for an 8-hr workday, and a 2 ppm STEL for 15-min as safe levels for occupational exposure (Plywood Association of Australasia, 2004); and
- New Zealand's "Occupational Exposure Limit" (OEL) is 1.0 ppm, not to be exceeded (Plywood Association of Australasia, 2004).

Lowering the amount of HCHO used in the manufacture of MDF, PB, and HWPW serves to reduce workplace HCHO exposures for workers in raw board manufacturing and resin plants. Moreover, end-user exposure would also be lowered due to the reduced HCHO content of raw boards.

## I. References

- Acheson ED, Barnes HR, Gardner MJ, Osmond C, Pannett B and Taylor CP (1984a). Cohort study of formaldehyde process workers. *Lancet* 2(8399): 403.
- Acheson ED, Barnes HR, Gardner MJ, Osmond C, Pannett B and Taylor CP (1984b). Formaldehyde in the British chemical industry. An occupational cohort study. *Lancet* 1(8377): 611-616.
- Acheson ED, Barnes HR, Gardner MJ, Osmond C, Pannett B and Taylor CP (1984c). Formaldehyde process workers and lung cancer. *Lancet* 1(8385): 1066-1067.
- Akbar-Khanzadeh F, Vaquerano MU, Akbar-Khanzadeh M and Bisesi MS (1994). Formaldehyde exposure, acute pulmonary response, and exposure control options in a gross anatomy laboratory. *Am J Ind Med* 26(1): 61-75.
- Alarie Y (1981). Toxicological evaluation of airborne chemical irritants and allergens using respiratory reflex reactions. Proceedings of the Inhalation Toxicology and Technology Symposium. Ann Arbor Sciences, Inc. 207-231. Kalamazoo (MI), October 23-24, 1980.
- Albert RE, Sellakumar AR, Laskin S, Kuschner M, Nelson N and Snyder CA (1982). Gaseous formaldehyde and hydrogen chloride induction of nasal cancer in the rat. *J Natl Cancer Inst* 68(4): 597-603.
- Alexandersson R and Hedenstierna G (1988). Respiratory hazards associated with exposure to formaldehyde and solvents in acid-curing paints. *Arch Environ Health* 43(3): 222-227.
- Alexandersson R and Hedenstierna G (1989). Pulmonary function in wood workers exposed to formaldehyde: a prospective study. *Arch Environ Health* 44(1): 5-11.
- Alexandersson R, Hedenstierna G and Kolmodin-Hedman B (1982). Exposure to formaldehyde: effects on pulmonary function. *Arch Environ Health* 37(5): 279-284.
- Amdur MO (1960). The response of guinea pigs to inhalation of formaldehyde and formic acid alone and with a sodium chloride aerosol. *Int J Air Pollut* 3: 201-20.
- Apfelbach R and Weiler E (1991). Sensitivity to odors in Wistar rats is reduced after low-level formaldehyde-gas exposure. *Naturwissenschaften* 78(5): 221-223.

Appelman LM, Woutersen RA, Zwart A, Falke HE and Feron VJ (1988). One-year inhalation toxicity study of formaldehyde in male rats with a damaged or undamaged nasal mucosa. *J Appl Toxicol* 8(2): 85-90.

Armstrong RW, Imrey PB, Lye MS, Armstrong MJ, Yu MC and Sani S (2000). Nasopharyngeal carcinoma in Malaysian Chinese: occupational exposures to particles, formaldehyde and heat. *Int J Epidemiol* 29(6): 991-998.

Arts JH, Rennen MA and de Heer C (2006). Inhaled formaldehyde: evaluation of sensory irritation in relation to carcinogenicity. *Regul Toxicol Pharmacol* 44(2): 144-160.

ATSDR. (1999). *Toxicological profile for formaldehyde*. Atlanta (GA): Agency for Toxic Substances and Disease Registry.

Auerbach C, Moutschen-Dahmen M and Moutschen J (1977). Genetic and cytogenetical effects of formaldehyde and related compounds. *Mutat Res* 39(3-4): 317-361.

Berke JH (1987). Cytologic examination of the nasal mucosa in formaldehyde-exposed workers. *J Occup Med* 29(8): 681-684.

Bertazzi PA, Pesatori A, Guercilena S, Consonni D and Zocchetti C (1989). [Carcinogenic risk for resin producers exposed to formaldehyde: extension of follow-up] *Med Lav* 80 (2): 111-122. In: As cited in IARC (2004) IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol 88 Formaldehyde, 2-Butoxyethanol and 1-tert-Butoxy-2-propanol. Summary of Data Reported and Evaluation. International Agency for Research on Cancer. Lyons, France.

Bertazzi PA, Pesatori AC, Radice L, Zocchetti C and Vai T (1986). Exposure to formaldehyde and cancer mortality in a cohort of workers producing resins. *Scand J Work Environ Health* 12(5): 461-468.

Blair A, Saracci R, Stewart PA, Hayes RB and Shy C (1990). Epidemiologic evidence on the relationship between formaldehyde exposure and cancer. *Scand J Work Environ Health* 16(6): 381-393.

Blair A, Stewart P, O'Berg M, Gaffey W, Walrath J, Ward J, Bales R, Kaplan S and Cubit D (1986). Mortality among industrial workers exposed to formaldehyde. *J Natl Cancer Inst* 76(6): 1071-1084.

Blair A, Stewart PA, Hoover RN, Fraumeni JF, Jr., Walrath J, O'Berg M and Gaffey W (1987). Cancers of the nasopharynx and oropharynx and formaldehyde exposure. *J Natl Cancer Inst* 78(1): 191-193.

Boysen M, Zadig E, Digernes V, Abeler V and Reith A (1990). Nasal mucosa in workers exposed to formaldehyde: a pilot study. *Br J Ind Med* 47(2): 116-121.

Broder I, Corey P, Brasher P, Lipa M and Cole P (1988). Comparison of health of occupants and characteristics of houses among control homes and homes insulated with urea formaldehyde foam. III. Health and house variables following remedial work. *Environ Res* 45(2): 179-203.

Burge PS, Harries MG, Lam WK, O'Brien IM and Patchett PA (1985). Occupational asthma due to formaldehyde. *Thorax* 40(4): 255-260.

California Air Resources Board (CARB). 1992. Final Report on the Identification of Formaldehyde as a Toxic Air Contaminant. Part A, Exposure Assessment. Technical Support Document, Stationary Source Division, Sacramento, CA. 89 pp.

CARB. 1993. The Identification of Federal Hazardous Air Pollutants as Toxic Air Contaminants. Staff Report, Stationary Source Division, Sacramento, CA. 8 pp.

CARB. 1997a. Methyl isocyanate. In: CARB. Toxic Air Contaminant List: Summaries, p. 667-669. Stationary Source Division, Sacramento, CA.

CARB. 1997b. Phenol. In: CARB. Toxic Air Contaminant List: Summaries, p. 767-770. Stationary Source Division, Sacramento, CA.

CARB. 2005. Indoor Air Pollution in California. Report to the Legislature, Pursuant to Health & Safety Code §39930. Research Division, Sacramento, CA. 248 pp.

Carpenter CP, Smyth HF, Jr. and Pozzani UC (1949). The assay of acute vapor toxicity, and the grading and interpretation of results on 96 chemical compounds. *J Ind Hyg Toxicol* 31(6): 343-346.

Casanova M, Morgan KT, Gross EA, Moss OR and Heck HA (1994). DNA-protein cross-links and cell replication at specific sites in the nose of F344 rats exposed subchronically to formaldehyde. *Fundam Appl Toxicol* 23(4): 525-536.

Coggon D, Harris EC, Poole J and Palmer KT (2003). Extended follow-up of a cohort of british chemical workers exposed to formaldehyde. *J Natl Cancer Inst* 95(21): 1608-1615.

Collins JJ and Lineker GA (2004). A review and meta-analysis of formaldehyde exposure and leukemia. *Regul Toxicol Pharmacol* 40(2): 81-91.

Conaway CC, Whysner J, Verna LK and Williams GM (1996). Formaldehyde mechanistic data and risk assessment: endogenous protection from DNA adduct formation. *Pharmacol Ther* 71(1-2): 29-55.

Conolly RB, Kimbell JS, Janszen DB and Miller FJ (2002). Dose response for formaldehyde-induced cytotoxicity in the human respiratory tract. *Regul Toxicol Pharmacol* 35(1): 32-43.

Cosma GN, Jamasbi R and Marchok AC (1988). Growth inhibition and DNA damage induced by benzo[a]pyrene and formaldehyde in primary cultures of rat tracheal epithelial cells. *Mutat Res* 201(1): 161-168.

Dalbey WE (1982). Formaldehyde and tumors in hamster respiratory tract. *Toxicology* 24(1): 9-14.

Dallas CE, Badeaux P, Theiss JC and Fairchild EJ (1989). The influence of inhaled formaldehyde on rat lung cytochrome P450. *Environ Res* 49(1): 50-59.

Delfino RJ, Gong H, Jr., Linn WS, Pellizzari ED and Hu Y (2003). Asthma symptoms in Hispanic children and daily ambient exposures to toxic and criteria air pollutants. *Environ Health Perspect* 111(4): 647-656.

Doi S, Suzuki S, Morishita M, Yamada M, Kanda Y, Torii S and Sakamoto T (2003). The prevalence of IgE sensitization to formaldehyde in asthmatic children. *Allergy* 58(7): 668-671.

Edling C, Hellquist H and Odkvist L (1988). Occupational exposure to formaldehyde and histopathological changes in the nasal mucosa. *Br J Ind Med* 45(11): 761-765.

Erdei E, Bobvos J, Brozik M, Paldy A, Farkas I, Vaskovi E and Rudnai P (2003). Indoor air pollutants and immune biomarkers among Hungarian asthmatic children. *Arch Environ Health* 58(6): 337-347.

Feinman SE (1988). Formaldehyde sensitivity and toxicity. Boca Raton (FL): CRC Press Inc.

Federal Register. 1992. Notices: Part VI., U.S. Environmental Protection Agency, Guidelines for Exposure Assessment. Vol. 57(104), pp. 22888-22938. May 29, 1992.

Feron VJ, Bruyntjes JP, Woutersen RA, Immel HR and Appelman LM (1988). Nasal tumours in rats after short-term exposure to a cytotoxic concentration of formaldehyde. *Cancer Lett* 39(1): 101-111.

Feron VJ, Til HP and Woutersen RA (1990). Formaldehyde must be considered a multipotential experimental carcinogen. *Toxicol Ind Health* 6(6): 637-639.

Forest Products Laboratory. 1999. Wood Handbook – Wood as an Engineering Material. General Technical Report, FPL-GTR-113. U.S. Department of Agriculture, Forest Service, Madison, WI. 463 pp.

Formaldehyde Council, Inc. 2004. Comments on California ARB Draft Report – Indoor Air Pollution in California. Submitted to Dorothy Shimer, Research Division, Sacramento, CA. 13 pp.

Formaldehyde Council, Inc. 2005a. Air toxics, formaldehyde, and risk characterization. Position Paper, 8 pp.

Formaldehyde Council, inc. 2005b. Formaldehyde. Fact Sheet. 2 pp.

Franklin P, Dingle P and Stick S (2000). Raised exhaled nitric oxide in healthy children is associated with domestic formaldehyde levels. *Am J Respir Crit Care Med* 161(5): 1757-1759.

Garrett MH, Hooper MA, Hooper BM, Rayment PR and Abramson MJ (1999). Increased risk of allergy in children due to formaldehyde exposure in homes. *Allergy* 54(4): 330-337.

Gerin M, Siemiatycki J, Nadon L, Dewar R and Krewski D (1989). Cancer risks due to occupational exposure to formaldehyde: results of a multi-site case-control study in Montreal. *Int J Cancer* 44(1): 53-58.

Gorski P, Tarkowski M, Krakowiak A and Kiec-Swierczynska M (1992). Neutrophil chemiluminescence following exposure to formaldehyde in healthy subjects and in patients with contact dermatitis. *Allergol Immunopathol (Madr)* 20(1): 20-23.

Grafstrom RC, Fornace A, Jr. and Harris CC (1984). Repair of DNA damage caused by formaldehyde in human cells. *Cancer Res* 44(10): 4323-4327.

Green DJ, Sauder LR, Kulle TJ and Bascom R (1987). Acute response to 3.0 ppm formaldehyde in exercising healthy nonsmokers and asthmatics. *Am Rev Respir Dis* 135(6): 1261-1266.

Hall A, Harrington JM and Aw TC (1991). Mortality study of British pathologists. *Am J Ind Med* 20(1): 83-89.

Hansen J and Olsen JH (1995). Formaldehyde and cancer morbidity among male employees in Denmark. *Cancer Causes Control* 6(4): 354-360.

Harving H, Korsgaard J, Pedersen OF, Molhave L and Dahl R (1990). Pulmonary function and bronchial reactivity in asthmatics during low-level formaldehyde exposure. *Lung* 168(1): 15-21.

Hauptmann M, Lubin JH, Stewart PA, Hayes RB and Blair A (2003). Mortality from lymphohematopoietic malignancies among workers in formaldehyde industries. *J Natl Cancer Inst* 95(21): 1615-1623.

Hauptmann M, Lubin JH, Stewart PA, Hayes RB and Blair A (2004). Mortality from solid cancers among workers in formaldehyde industries. *Am J Epidemiol* 159(12): 1117-1130.

Hayes RB, Blair A, Stewart PA, Herrick RF and Mahar H (1990). Mortality of U.S. embalmers and funeral directors. *Am J Ind Med* 18(6): 641-652.

Hayes RB, Raatgever JW, de Bruyn A and Gerin M (1986). Cancer of the nasal cavity and paranasal sinuses, and formaldehyde exposure. *Int J Cancer* 37(4): 487-492.

Hemminki K, Kyyronen P and Lindbohm ML (1985). Spontaneous abortions and malformations in the offspring of nurses exposed to anaesthetic gases, cytostatic drugs, and other potential hazards in hospitals, based on registered information of outcome. *J Epidemiol Community Health* 39(2): 141-147.

Hendrick DJ and Lane DJ (1977). Occupational formalin asthma. *Br J Ind Med* 34(1): 11-18.

Hildesheim A, Dosemeci M, Chan CC, Chen CJ, Cheng YJ, Hsu MM, Chen IH, Mittl BF, Sun B, Levine PH, Chen JY, Brinton LA and Yang CS (2001). Occupational exposure to wood, formaldehyde, and solvents and risk of nasopharyngeal carcinoma. *Cancer Epidemiol Biomarkers Prev* 10(11): 1145-1153.

Holmstrom M and Wilhelmsson B (1988). Respiratory symptoms and pathophysiological effects of occupational exposure to formaldehyde and wood dust. *Scand J Work Environ Health* 14(5): 306-311.

Holmstrom M, Wilhelmsson B and Hellquist H (1989). Histological changes in the nasal mucosa in rats after long-term exposure to formaldehyde and wood dust. *Acta Otolaryngol* 108(3-4): 274-283.

Homma Y, Nowels K and Oyasu R (1986). Effects of formalin-induced injuries on urinary bladder carcinogenesis. *Cancer Lett* 32(2): 117-123.

Horton AW, Tye R and Stemmer KL (1963). Experimental carcinogenesis of the lung. Inhalation of gaseous formaldehyde or an aerosol of coal tar by C3H mice. *J Natl Cancer Inst* 30: 31-43.

Horvath EP, Jr., Anderson H, Jr., Pierce WE, Hanrahan L and Wendlick JD (1988). Effects of formaldehyde on the mucous membranes and lungs. A study of an industrial population. *Jama* 259(5): 701-707.

IARC (2004a). IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol. 88 Formaldehyde, 2-Butoxyethanol and 1-tert-Butoxy-2-propanol. Summary of Data Reported and Evaluation. *Cancer I. A. f. R. o. IARC Monographs*. Lyon, France: International Agency for Research on Cancer.

IARC (2004b). IARC Monographs on Formaldehyde, Vol. 62. Lyon, France: International Agency for Research on Cancer.

Iversen OH, Ljunggren S and Olsen WM (1988). The early effects of a single application of acetone and various doses of 7,12-dimethylbenz(alpha)anthracene on CD-1 and hairless mouse epidermis. A cell kinetic study of so-called initiation and complete carcinogenesis (initiation plus promotion) in chemical skin tumor induction. *APMIS Suppl* 2: 7-80.

John EM, Savitz DA and Shy CM (1994). Spontaneous abortions among cosmetologists. *Epidemiology* 5(2): 147-155.

Kamata E, Nakadate M, Uchida O, Ogawa Y, Suzuki S, Kaneko T, Saito M and Kurokawa Y (1997). Results of a 28-month chronic inhalation toxicity study of formaldehyde in male Fisher-344 rats. *J Toxicol Sci* 22(3): 239-254.

Kerfoot EJ and Mooney TF (1975). Formaldehyde and paraformaldehyde study in funeral homes. *Am Ind Hyg Assoc J* 36(7): 533-537.

Kerns WD, Pavkov KL, Donofrio DJ, Gralla EJ and Swenberg JA (1983). Carcinogenicity of formaldehyde in rats and mice after long-term inhalation exposure. *Cancer Res* 43(9): 4382-4392.

Kilburn KH, Warshaw R and Thornton JC (1989). Pulmonary function in histology technicians compared with women from Michigan: effects of chronic low dose formaldehyde on a national sample of women. *Br J Ind Med* 46(7): 468-472.

Kimbell JS, Gross EA, Richardson RB, Conolly RB and Morgan KT (1997). Correlation of regional formaldehyde flux predictions with the distribution of formaldehyde-induced squamous metaplasia in F344 rat nasal passages. *Mutat Res* 380(1-2): 143-154.

Kitaeva LV, Kitaev EM and Pimenova MN (1990). [The cytopathic and cytogenetic sequelae of chronic inhalational exposure to formaldehyde on female germ cells and bone marrow cells in rats]. *Tsitologija* 32(12): 1212-1216.

Kriebel D, Myers D, Cheng M, Woskie S and Cocanour B (2001). Short-term effects of formaldehyde on peak expiratory flow and irritant symptoms. *Arch Environ Health* 56(1): 11-18.

Krzyzanowski M, Quackenboss JJ and Lebowitz MD (1990). Chronic respiratory effects of indoor formaldehyde exposure. *Environ Res* 52(2): 117-125.

Kulle TJ, Sauder LR, Hebel JR, Green DJ and Chatham MD (1987). Formaldehyde dose-response in healthy nonsmokers. *Japca* 37(8): 919-924.

Levine RJ, Andjelkovich DA and Shaw LK (1984). The mortality of Ontario undertakers and a review of formaldehyde-related mortality studies. *J Occup Med* 26(10): 740-746.

Liebling T, Rosenman KD, Pastides H, Griffith RG and Lemeshow S (1984). Cancer mortality among workers exposed to formaldehyde. *Am J Ind Med* 5(6): 423-428.

Lindbohm ML, Hemminki K, Bonhomme MG, Anttila A, Rantala K, Heikkila P and Rosenberg MJ (1991). Effects of paternal occupational exposure on spontaneous abortions. *Am J Public Health* 81(8): 1029-1033.

Linos A, Blair A, Cantor KP, Burmeister L, VanLier S, Gibson RW, Schuman L and Everett G (1990). Leukemia and non-Hodgkin's lymphoma among embalmers and funeral directors. *J Natl Cancer Inst* 82(1): 66.

Liu KS, Huang FY, Hayward SB, Wesolowski J and Sexton K (1991). Irritant effects of formaldehyde exposure in mobile homes. *Environ Health Perspect* 94: 91-94.

Logue JN, Barrick MK and Jessup GL, Jr. (1986). Mortality of radiologists and pathologists in the Radiation Registry of Physicians. *J Occup Med* 28(2): 91-99.

Luce D, Leclerc A, Begin D, Demers PA, Gerin M, Orlowski E, Kogevinas M, Belli S, Bugel I, Bolm-Audorff U, Brinton LA, Comba P, Hardell L, Hayes RB, Magnani C, Merler E, Preston-Martin S, Vaughan TL, Zheng W and Boffetta P (2002). Sinonasal cancer and occupational exposures: a pooled analysis of 12 case-control studies. *Cancer Causes Control* 13(2): 147-157.

Malaka T and Kodama AM (1990). Respiratory health of plywood workers occupationally exposed to formaldehyde. *Arch Environ Health* 45(5): 288-294.

Malker HS, McLaughlin JK, Weiner JA, Silverman DT, Blot WJ, Ericsson JL and Fraumeni JF, Jr. (1990). Occupational risk factors for nasopharyngeal cancer in Sweden. *Br J Ind Med* 47(3): 213-214.

Mannino DM, Homa DM, Pertowski CA, Ashizawa A, Nixon LL, Johnson CA, Ball LB, Jack E and Kang DS (1998). Surveillance for asthma--United States, 1960-1995. *MMWR CDC Surveill Summ* 47(1): 1-27.

Maronpot RR, Miller RA, Clarke WJ, Westerberg RB, Decker JR and Moss OR (1986). Toxicity of formaldehyde vapor in B6C3F1 mice exposed for 13 weeks. *Toxicology* 41(3): 253-266.

Martin WJ (1990). A teratology study of inhaled formaldehyde in the rat. *Reprod Toxicol* 4(3): 237-239.

Massachusetts Toxics Use Reduction Institute. Not Dated. 4,4'-Methylene Diphenyl Isocyanate. Massachusetts Chemical Fact Sheet, 4 pp.

Mclsaac J. 2005. Columbia Forest Products to Convert Standard Hardwood Plywood Production to Eliminate All Formaldehyde. Press Release, Columbia Forest Products, Portland, OR. 1 pp.

Merk O and Speit G (1998). Significance of formaldehyde-induced DNA-protein crosslinks for mutagenesis. *Environ Mol Mutagen* 32(3): 260-268.

Monteiro-Riviere NA and Popp JA (1986). Ultrastructural evaluation of acute nasal toxicity in the rat respiratory epithelium in response to formaldehyde gas. *Fundam Appl Toxicol* 6(2): 251-262.

Monticello TM, Swenberg JA, Gross EA, Leininger JR, Kimbell JS, Seilkop S, Starr TB, Gibson JE and Morgan KT (1996). Correlation of regional and nonlinear formaldehyde-induced nasal cancer with proliferating populations of cells. *Cancer Res* 56(5): 1012-1022.

Morgan KT, Gross EA and Patterson DL (1986). Distribution, progression, and recovery of acute formaldehyde-induced inhibition of nasal mucociliary function in F-344 rats. *Toxicol Appl Pharmacol* 86(3): 448-456.

Muller P, Raabe G and Schumann D (1978). Leukoplakia induced by repeated deposition of formalin in rabbit oral mucosa. Long-term experiments with a new "oral tank". *Exp Pathol (Jena)* 16(1-6): 36-42.

Nagorny PA, Sudakova Zh A and Shchablenko SM (1979). [General toxic and allergic action of formaldehyde]. *Gig Tr Prof Zabol*(1): 27-30.

Nielsen GD, Hougaard KS, Larsen ST, Hammer M, Wolkoff P, Clausen PA, Wilkins CK and Alarie Y (1999). Acute airway effects of formaldehyde and ozone in BALB/c mice. *Hum Exp Toxicol* 18(6): 400-409.

NIOSH. 2005. Methylene bisphenyl Isocyanate. Accessed: 8 March 2007.  
From: <http://www.cdc.gov/niosh/npg/npgd0413.html>

Nordman H, Keskinen H and Tuppurainen M (1985). Formaldehyde asthma--rare or overlooked? *J Allergy Clin Immunol* 75(1 Pt 1): 91-99.

OECD. 1998. Melamine: CAS No. 108-78-1. SIDS Initial Assessment Report for the 8<sup>th</sup> SIAM. From: <http://www.inchem.org/documents/sids/sids/108781.pdf>  
Accessed: 19 May 2005.

Office of Environmental Health Hazard Assessment (OEHHA). 1999. Determination of Acute Reference Exposure Levels for Airborne Toxicants. C 132-145. From: [http://www.oehha.ca.gov/air/acute\\_rels/pdf/50000a.pdf](http://www.oehha.ca.gov/air/acute_rels/pdf/50000a.pdf)  
Accessed: 6 March, 2007.

OEHHA. 2000. All acute reference exposure levels adopted by OEHHA as of May 2000. From: [http://www.oehha.ca.gov/air/acute\\_rels/allacrels.html](http://www.oehha.ca.gov/air/acute_rels/allacrels.html)  
Accessed: 8 February 2007.

OEHHA. 2000. Methylene Diphenyl Isocyanate. Chronic Toxicity Summary. In: Determination of Noncancer Chronic Reference Exposure Levels, Batch 2A, p. A-143 to A148. OEHHA, Oakland, CA.

OEHHA. (2001). Prioritization of Toxic Air Contaminants - Children's Health Protection Act - Final Report. OEHHA, Oakland, CA. From:  
[http://www.oehha.ca.gov/air/toxic\\_contaminants/SB25finalreport.html](http://www.oehha.ca.gov/air/toxic_contaminants/SB25finalreport.html).

OEHHA. 2003. The Air Toxics Hot Spots Program Guidance Manual for Preparation of Health Risk Assessments. Appendix I: Calculation Examples for Estimating Potential Health Impacts. OEHHA, Oakland, CA. 11 pp.

OEHHA. 2005a. Appendix A: Hot Spots Unit Risk and Cancer Potency Values. In: OEHHA. Air Toxics Hot Spots Program Risk Assessment Guidelines. Part II. Technical Support Document for Describing Available Cancer Potency Factors.

OEHHA. 2005b. All chronic reference exposure levels adopted by OEHHA as of February 2005. From: [http://www.oehha.ca.gov/air/chronic\\_rels/allchrels.html](http://www.oehha.ca.gov/air/chronic_rels/allchrels.html)  
Accessed: 8 February 2007.

Olsen JH and Asnaes S (1986). Formaldehyde and the risk of squamous cell carcinoma of the sinonasal cavities. *Br J Ind Med* 43(11): 769-774.

Olsen JH and Dossing M (1982). Formaldehyde induced symptoms in day care centers. *Am Ind Hyg Assoc J* 43(5): 366-370.

Olsen JH, Jensen SP, Hink M, Faurbo K, Breum NO and Jensen OM (1984). Occupational formaldehyde exposure and increased nasal cancer risk in man. *Int J Cancer* 34(5): 639-644.

PFS Research Foundation. 2001. Formaldehyde emissions from wood-based panels. *Techtips*, 2(6): 1.

Pinkerton LE, Hein MJ and Stayner LT (2004). Mortality among a cohort of garment workers exposed to formaldehyde: an update. *Occup Environ Med* 61(3): 193-200.

Plywood Association of Australasia, Ltd. 2004. Formaldehyde emissions from plywood and laminated veneer lumber. Comments on IARB review. From: <http://www.plywoodassn.com.au> Accessed: 10 August 2005.

Porter JA (1975). Letter: Acute respiratory distress following formalin inhalation. *Lancet* 2(7935): 603-604.

Research Triangle Institute. 1998. Concentrations of Selected Air Pollutants Inside California Vehicles. Final Report, CARB Contract No. 95-339, Research Division, Sacramento, CA. 155 pp.

Riedel F, Hasenauer E, Barth PJ, Kozirowski A and Rieger CH (1996). Formaldehyde exposure enhances inhalative allergic sensitization in the guinea pig. *Allergy* 51(2): 94-9.

Ritchie IM and Lehnen RG (1987). Formaldehyde-related health complaints of residents living in mobile and conventional homes. *Am J Public Health* 77(3): 323-328.

Roush GC, Walrath J, Stayner LT, Kaplan SA, Flannery JT and Blair A (1987). Nasopharyngeal cancer, sinonasal cancer, and occupations related to formaldehyde: a case-control study. *J Natl Cancer Inst* 79(6): 1221-1224.

Rumchev KB, Spickett JT, Bulsara MK, Phillips MR and Stick SM (2002). Domestic exposure to formaldehyde significantly increases the risk of asthma in young children. *Eur Respir J* 20(2): 403-408.

Rusch GM, Clary JJ, Rinehart WE and Bolte HF (1983). A 26-week inhalation toxicity study with formaldehyde in the monkey, rat, and hamster. *Toxicol Appl Pharmacol* 68(3): 329-343.

Saillenfait AM, Bonnet P and de Ceaurriz J (1989). The effects of maternally inhaled formaldehyde on embryonal and foetal development in rats. *Food Chem Toxicol* 27(8): 545-548.

Salem H and Cullumbine H (1960). Inhalation toxicities of some aldehydes. *Toxicol Appl Pharmacol* 2: 183-187.

Sauder LR, Chatham MD, Green DJ and Kulle TJ (1986). Acute pulmonary response to formaldehyde exposure in healthy nonsmokers. *J Occup Med* 28(6): 420-424.

Sauder LR, Green DJ, Chatham MD and Kulle TJ (1987). Acute pulmonary response of asthmatics to 3.0 ppm formaldehyde. *Toxicol Ind Health* 3(4): 569-578.

Schachter EN, Witek TJ, Jr., Brody DJ, Tosun T, Beck GJ and Leaderer BP (1987). A study of respiratory effects from exposure to 2.0 ppm formaldehyde in occupationally exposed workers. *Environ Res* 44(2): 188-205.

Schachter EN, Witek TJ, Jr., Tosun T, Leaderer BP and Beck GJ (1986). A study of respiratory effects from exposure to 2 ppm formaldehyde in healthy subjects. *Arch Environ Health* 41(4): 229-39.

Sellakumar AR, Snyder CA, Solomon JJ and Albert RE (1985). Carcinogenicity of formaldehyde and hydrogen chloride in rats. *Toxicol Appl Pharmacol* 81(3 Pt 1): 401-6.

Shaham J, Bomstein Y, Gurvich R, Rashkovsky M and Kaufman Z (2003). DNA-protein crosslinks and p53 protein expression in relation to occupational exposure to formaldehyde. *Occup Environ Med* 60(6): 403-9.

Shaham J, Bomstein Y, Meltzer A, Kaufman Z, Palma E and Ribak J (1996). DNA--protein crosslinks, a biomarker of exposure to formaldehyde--in vitro and in vivo studies. *Carcinogenesis* 17(1): 121-5.

Shaham J, Bomstein Y, Melzer A and Ribak J (1997). DNA-Protein Crosslinks and Sister Chromatid Exchanges as Biomarkers of Exposure to Formaldehyde. *Int J Occup Environ Health* 3(2): 95-104.

Shaham J, Gurvich R and Kaufman Z (2002). Sister chromatid exchange in pathology staff occupationally exposed to formaldehyde. *Mutat Res* 514(1-2): 115-23.

Sheppard D, Eschenbacher WL and Epstein J (1984). Lack of bronchomotor response to up to 3 ppm formaldehyde in subjects with asthma. *Environ Res* 35(1): 133-9.

Sherman MH and AT Hodgson. (2003). Formaldehyde as a basis for residential ventilation rates. *Indoor Air* 2004: 14: 2-8.

Wikipedia Contributors. (2007). Soybean. From: <http://en.wikipedia.org/wiki/soybean>. Accessed: 6 March, 2007.

Sim VM and Pattle RE (1957). Effect of possible smog irritants on human subjects. *J Am Med Assoc* 165(15): 1908-13.

Skog E (1950). A toxicological investigation of lower aliphatic aldehydes. I. toxicity of formaldehyde, acetaldehyde, propionaldehyde butyraldehyde; as well as acrolein and crotonaldehyde. *Acta Pharmacol Toxicol* 6: 299-318.

Smedje G and Norback D (2001a). Incidence of asthma diagnosis and self-reported allergy in relation to the school environment--a four-year follow-up study in schoolchildren. *Int J Tuberc Lung Dis* 5(11): 1059-1066.

Smedje G and Norback D (2001b). Irritants and allergens at school in relation to furnishings and cleaning. *Indoor Air* 11(2): 127-133.

Smedje G, Norback D and Edling C (1997). Asthma among secondary schoolchildren in relation to the school environment. *Clin Exp Allergy* 27(11): 1270-8.

Soffritti M, Belpoggi F, Lambertin L, Lauriola M, Padovani M and Maltoni C (2002). Results of long-term experimental studies on the carcinogenicity of formaldehyde and acetaldehyde in rats. *Ann N Y Acad Sci* 982: 87-105.

Soffritti M, Maltoni C, Maffei F and Biagi R (1989). Formaldehyde: an experimental multipotential carcinogen. *Toxicol Ind Health* 5(5): 699-730.

Solomons K and Cochrane JW (1984a). Formaldehyde toxicity. Part I. Occupational exposure and a report of 5 cases. *S Afr Med J* 66(3): 101-2.

Speit G and Merk O (2002). Evaluation of mutagenic effects of formaldehyde in vitro: detection of crosslinks and mutations in mouse lymphoma cells. *Mutagenesis* 17(3): 183-187.

Srivastava AK, Gupta BN, Bihari V, Gaur JS, Mathur N and Awasthi VK (1992). Clinical studies of employees in a sheet-forming process at a paper mill. *Vet Hum Toxicol* 34(6): 525-7.

Stayner L, Smith AB, Reeve G, Blade L, Elliott L, Keenlyside R and Halperin W (1985). Proportionate mortality study of workers in the garment industry exposed to formaldehyde. *Am J Ind Med* 7(3): 229-40.

Stayner LT, Elliott L, Blade L, Keenlyside R and Halperin W (1988). A retrospective cohort mortality study of workers exposed to formaldehyde in the garment industry. *Am J Ind Med* 13(6): 667-81.

Sterling TD and Weinkam JJ (1988). Reanalysis of lung cancer mortality in a National Cancer Institute study on mortality among industrial workers exposed to formaldehyde. *J Occup Med* 30(11): 895-901.

Sterling TD and Weinkam JJ (1989). Reanalysis of lung cancer mortality in a National Cancer Institute Study on "Mortality among industrial workers exposed to formaldehyde". *Exp Pathol* 37(1-4): 128-32.

Stroup NE, Blair A and Erikson GE (1986). Brain cancer and other causes of death in anatomists. *J Natl Cancer Inst* 77(6): 1217-24.

Swenberg J, Kerns W, Pavkov K, Mitchell R and Gralla EJ (1980a). Carcinogenicity of formaldehyde vapor: interim findings in a long-term bioassay of rats and mice. *Dev Toxicol Environ Sci* 8: 283-6.

Swenberg JA, Barrow CS, Boreiko CJ, Heck HD, Levine RJ, Morgan KT and Starr TB (1983). Non-linear biological responses to formaldehyde and their implications for carcinogenic risk assessment. *Carcinogenesis* 4(8): 945-52.

Swenberg JA, Kerns WD, Mitchell RI, Gralla EJ and Pavkov KL (1980b). Induction of squamous cell carcinomas of the rat nasal cavity by inhalation exposure to formaldehyde vapor. *Cancer Res* 40(9): 3398-402.

Swiecichowski AL, Long KJ, Miller ML and Leikauf GD (1993). Formaldehyde-induced airway hyperreactivity in vivo and ex vivo in guinea pigs. *Environ Res* 61(2): 185-99.

Takahashi M, Hasegawa R, Furukawa F, Toyoda K, Sato H and Hayashi Y (1986). Effects of ethanol, potassium metabisulfite, formaldehyde and hydrogen peroxide on gastric carcinogenesis in rats after initiation with N-methyl-N'-nitro-N-nitrosoguanidine. *Jpn J Cancer Res* 77(2): 118-24.

Taskinen H, Kyyronen P, Hemminki K, Hoikkala M, Lajunen K and Lindbohm ML (1994). Laboratory work and pregnancy outcome. *J Occup Med* 36(3): 311-9.

Thrasher JD, Broughton A and Madison R (1990). Immune activation and autoantibodies in humans with long-term inhalation exposure to formaldehyde. *Arch Environ Health* 45(4): 217-23.

Thrasher JD, Wojdani A, Cheung G and Heuser G (1987). Evidence for formaldehyde antibodies and altered cellular immunity in subjects exposed to formaldehyde in mobile homes. *Arch Environ Health* 42(6): 347-50.

Til HP, Woutersen RA, Feron VJ, Hollanders VH, Falke HE and Clary JJ (1989). Two-year drinking-water study of formaldehyde in rats. *Food Chem Toxicol* 27(2): 77-87.

Tobe M, Kaneko T, Uchida Y, Kamata E, Ogawa Y, Ikeda Y and Saito M (1985). Studies on the inhalation toxicity of formaldehyde. Report of the National Sanitary and Medical Laboratory Service. Toxicity Department of the Organism Safety Research Center. Tokyo p 94. As cited in IARC (2004) IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol 88 Formaldehyde, 2-Butoxyethanol and 1-tert-Butoxy-2-propanol. Summary of Data Reported and Evaluation.

Tobe M, Naito K and Kurokawa Y (1989). Chronic toxicity study on formaldehyde administered orally to rats. *Toxicology* 56(1): 79-86.

Uba G, Pachorek D, Bernstein J, Garabrant DH, Balmes JR, Wright WE and Amar RB (1989). Prospective study of respiratory effects of formaldehyde among healthy and asthmatic medical students. *Am J Ind Med* 15(1): 91-101.

USEPA. (1987). *Assessment of Health Risks to Garment Workers and Certain Home Residents from exposure to Formaldehyde*. U.S. Environmental Protection Agency, Washington D.C.

USEPA. Not Dated. Methylene Diphenyl Diisocyanate (monomeric MDI) and polymeric MDI (PMDI) (CASRN 101-68-8, 9016-87-9). From: <http://www.epa.gov/IRIS/subst/0529.htm> Accessed: 8 March 2007.

University of California, Berkeley (UCB). 1991a. Activity Patterns of California Residents. Final Report, CARB Contract No. A6-177-33, Research Division, Sacramento, CA. 63 pp.

UCB. 1991b. Study of Children's Activity Patterns. Final Report, CARB Contract No. A733-149, Research Division, Sacramento, CA. 83 pp.

Vaughan TL, Stewart PA, Teschke K, Lynch CF, Swanson GM, Lyon JL and Berwick M (2000). Occupational exposure to formaldehyde and wood dust and nasopharyngeal carcinoma. *Occup Environ Med* 57(6): 376-84.

Vaughan TL, Strader C, Davis S and Daling JR (1986a). Formaldehyde and cancers of the pharynx, sinus and nasal cavity: I. Occupational exposures. *Int J Cancer* 38(5): 677-83.

Vaughan TL, Strader C, Davis S and Daling JR (1986b). Formaldehyde and cancers of the pharynx, sinus and nasal cavity: II. Residential exposures. *Int J Cancer* 38(5): 685-8.

Wallenstein G, Rebohle E, Bergmann I, Voigt U and Schneider WD (1978). [Occupational diseases of the respiratory system due to chemical substances with potential allergen effects]. *Dtsch Gesundheitsw* 33(24): 1119-23.

Walrath J and Fraumeni JF, Jr. (1983). Mortality patterns among embalmers. *Int J Cancer* 31(4): 407-11.

Walrath J and Fraumeni JF, Jr. (1984). Cancer and other causes of death among embalmers. *Cancer Res* 44(10): 4638-41.

Wantke F, Demmer CM, Tappler P, Gotz M and Jarisch R (1996). Exposure to gaseous formaldehyde induces IgE-mediated sensitization to formaldehyde in school-children. *Clin Exp Allergy* 26(3): 276-80.

Watanabe F, Matsunaga T, Soejima T and Iwata Y (1954). [Study on the carcinogenicity of aldehyde. I. Experimentally produced rat sarcomas by repeated injections of aqueous solution of formaldehyde.] 45 (2-3): 451-2. In: As cited in IARC (2004) IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Vol 88 Formaldehyde, 2-Butoxyethanol and 1-tert-Butoxy-2-propanol. Summary of Data Reported and Evaluation. International Agency for Research on Cancer. Lyons, France.

Weber-Tschopp A, Fischer T and Grandjean E (1977). [Irritating effects of formaldehyde on man (author's transl)]. *Int Arch Occup Environ Health* 39(4): 207-18.

West S, Hildesheim A and Dosemeci M (1993). Non-viral risk factors for nasopharyngeal carcinoma in the Philippines: results from a case-control study. *Int J Cancer* 55(5): 722-7.

Wilhelmsson B and Holmstrom M (1992). Possible mechanisms of formaldehyde-induced discomfort in the upper airways. *Scand J Work Environ Health* 18(6): 403-7.

Wilmer JW, Woutersen RA, Appelman LM, Leeman WR and Feron VJ (1989). Subchronic (13-week) inhalation toxicity study of formaldehyde in male rats: 8-hour intermittent versus 8-hour continuous exposures. *Toxicol Lett* 47(3): 287-93.

Witek TJ, Jr., Schachter EN, Tosun T, Beck GJ and Leaderer BP (1987). An evaluation of respiratory effects following exposure to 2.0 ppm formaldehyde in asthmatics: lung function, symptoms, and airway reactivity. *Arch Environ Health* 42(4): 230-7.

Woutersen RA, van Garderen-Hoetmer A, Bruijntjes JP, Zwart A and Feron VJ (1989). Nasal tumours in rats after severe injury to the nasal mucosa and prolonged exposure to 10 ppm formaldehyde. *J Appl Toxicol* 9(1): 39-46.

Zwart A, Woutersen RA, Wilmer JW, Spit BJ and Feron VJ (1988). Cytotoxic and adaptive effects in rat nasal epithelium after 3-day and 13-week exposure to low concentrations of formaldehyde vapour. *Toxicology* 51(1): 87-99.

## **VIII. Economic Impacts of the Proposed Airborne Toxic Control Measure**

This chapter presents the estimated costs and economic impacts associated with the implementation of the proposed ATCM to control HCHO emissions from HWPW, PB, MDF, and finished goods that contain those materials. An overview of composite wood manufacturing in the U.S. is provided as a basis for assessing the financial ability of manufacturers to produce products that comply with the proposed emission standards. An explanation of the cost-basis is then presented where estimates of the least-costly (i.e., use of “drop-in” technology) and most-costly (i.e., outdated plants) options are presented, along with projected impacts to small producers.

The total cost of compliance to the composite wood manufacturing industry was estimated by multiplying the projected per panel increases in HWPW, PB, and MDF by the amount sold to California. These costs would be borne by those manufacturers that currently do not produce products that comply with the proposed Phase 1 or Phase 2 standards and plan to continue to sell products into the California market. The projected impacts to downstream businesses such as distributors, importers, fabricators, and retailers are also discussed.

### **A. Background**

#### **1. Composite Wood Product Manufacturing in the U.S.**

##### **a. Particleboard**

In North America (U.S. and Canada), PB manufacturing is a billion-plus dollar industry (Composite Panel Association, 2006). In 2005, North American PB shipments ( $\approx$  production) of industrial and flooring products were approximately 6-billion ft<sup>2</sup> (approximately 10-million m<sup>3</sup>) with an estimated value of \$1.65 billion (i.e., the average cost of PB was \$311 per thousand ft<sup>2</sup>).

In North America, the interests of PB and MDF manufacturers are largely represented by the Composite Panel Association (Gaithersburg, Maryland). An affiliated organization, the 180-plus member Composite Wood Council, brings together PB and MDF panel producers, furniture and cabinet manufacturers, distributors, suppliers, and others to disseminate to a broader audience, the attributes of composite wood products. The Composite Panel Association’s current membership includes 37 of the leading U.S., Canadian, and Mexican manufacturers, collectively representing over 95% of total North American manufacturing capacity (Table VIII-1) (Composite Panel Association, Not Dated). This number is consistent with estimates for 1997-98, when the number of U.S. mills was thought to be 45 to 51 (Sellers, 2001; USEPA, 2002), which may account for the small percentage of manufacturers that are not members of the Composite Panel Association. Seven companies that manufacture PB in North

America also operate MDF mills (i.e., ATC Panels, Flakeboard, Georgia-Pacific, SierraPine, Temple-Inland, Uniboard, Weyerhaeuser).

In the CARB 2003 Survey, responses were received from 20-mills regarding the manufacture of PB (CARB, 2003). The range in reported annual production amounts was 36- to 350-million ft<sup>2</sup>, where the median annual production of the 20-mills was 130-million ft<sup>2</sup>. In an attempt to classify the mills as either small, mid-size, or large, for purposes of this report, small manufacturers were designated as mills that produced less than 110-million ft<sup>2</sup> (17%), mid-size manufacturers between 110- to 170-million ft<sup>2</sup> (37%), and large manufacturers more than 170-million ft<sup>2</sup> (46%). Regardless of whether a mill was small, mid-size, or large, these facilities represent enterprises with a minimum of 50 or more employees. Similar distinctions were made for the 56-companies subject to the USEPA's National Emission Standard for Hazardous Air Pollutants rulemaking for composite wood product manufacturing: 23% of facilities had less than 100-employees, 54% had between 100- to 249-employees, and 23% had more than 250-employees (USEPA, 2002).

Besides number of employees, questions arise with respect to mill age and the vintage of equipment being used at present, which will likely determine the extent of modification needed to produce PB that complies with proposed Phase 1 and Phase 2 standards in 2009 to 2012. It is not clear what portion of the industry has already expended resources to upgrade their facilities over the past 10-years. Seemingly, as this is an industry that is made up principally of mid-size and large companies, those that choose to make the necessary improvements to produce low-emission PB for the California market will do so after careful consideration of the potential economic impacts.

No.	Company (No. Mills)	Mill Location(s)
1	ATC Panels, Inc. (2)	Franklin, VA; Moncure, NC
2	Boise Cascade Corp. (1)	La Grande, OR
3	CanPar Industries (1)	Grand Forks, British Columbia
4	Collins Products, LLC (1)	Klamath Falls, OR
5	Columbia Forest Products (1)	Hearst, Ontario
6	Duraplay de Parral, S.A. de C.V. (1)	Parral, Chihuahua
7	Fibratech Mfg., Inc. (1)	Atikokan, Ontario
8	Flakeboard Co., Ltd. (1)	St. Stephen, New Brunswick
9	Florida Plywoods, Inc. (1)	Greenville, Florida
10	Georgia-Pacific Corp. (5)	Gaylord, MI; Louisville, MS; Russellville, SC; Taylorsville, MS; Vienna, GA
11	GreenTech Panels, LLC (1)	Minden, LA

Table VIII-1. Continued		
No.	Company (No. Mills)	Mill Location(s)
12	Marshfield Door Systems, Inc. (1)	Marshfield, WI
13	Merillat Industries, Inc. (1)	Rapid City, SD
14	No. Engineered Wood Products (1)	Smithers, British Columbia
15	Panolam Industries International (1)	Huntsville, Ontario
16	Potlatch Forest Products, Corp. (1)	Post Falls, ID
17	Rexcel S.A. de C.V. (2)	Chihuahua, Chihuahua; Zitacuaro, Michoacan
18	Roseburg Forest Products Co. (2)	Dillard, OR; Missoula, MT
19	SierraPine, Ltd. (3)	Adel, GA; Martell, CA; Springfield, OR
20	Tafisa Canada & Co., Ltd. (1)	Lac-Megantic, Quebec
21	Temple-Inland (4)	Diboll, TX; Hope, AR; Monroeville, AL; Thomson, GA
22	Timber Products Co. (1)	Medford, OR
23	Uniboard Canada, Inc. (2)	Sayabec, Quebec; Val d'Or, Quebec
24	Webb Furniture Enterprises, Inc. (1)	Galax, VA
25	Weyerhaeuser Co. (3)	Albany, OR; Bennetsville, SC; Simsboro, LA
Source: Composite Panel Association (Not Dated).		

b. Medium Density Fiberboard

In terms of total North American production, the amount of MDF produced in 2005 was less than half of the amount of PB production (i.e., 2.6-billion vs. 5.6-billion ft<sup>2</sup>) (Composite Panel Association, 2006). The total value of the MDF was estimated to be \$1-billion, about 63% of the value of PB production. Per thousand ft<sup>2</sup>, the average cost of MDF was about 40% higher than PB (i.e., \$435 vs. \$311) in 2005. The Composite Panel Association currently lists 26-mills among its member companies (Table VIII-2) (Composite Panel Association, Not Dated).

In the CARB 2003 Survey, responses were received from 12-mills regarding MDF production volume (CARB, 2003). The range in reported annual production amounts was 18- to 204-million ft<sup>2</sup>, where the median annual production of the 12-mills was 107-million ft<sup>2</sup>. For the MDF cost analysis we classified the MDF mills as either small, mid-size, or large; in this case, small manufacturers were designated as mills that produced less than 100-million ft<sup>2</sup> (18%), mid-size manufacturers between 100- to 125-million ft<sup>2</sup> (38%), and large manufacturers more than 125-million ft<sup>2</sup> (43%). Like PB-mills, small, mid-size, and large MDF-mills appear to be fairly substantive facilities requiring 50-plus employees.

Table VIII-2. Medium Density Fiberboard Manufacturers in the Composite Panel Association		
No.	Company (No. Mills)	Mill(s)
1	ATC Panels, Inc. (2)	Clarion, PA; Pembroke, Ontario
2	Basset Fiberboard (1)	Bassett, VA
3	CMI/CraftMaster Mfg., Inc. (1)	Towanda, PA
4	Del-Tin Fiber, LLC (1)	El Dorado, AR
5	Flakeboard Co., Ltd. (2)	St. Stephen, New Brunswick; Sault Ste. Marie, Ontario
6	Georgia-Pacific Corp. (2)	Holly Hill, SC; Monticello, GA
7	Great Lakes MDF, LLC (1)	Lackawanna, NY
8	Langboard, Inc. (1)	Willacochee, GA
9	Norbord Industries, Inc. (1)	Deposit, NY
10	Pan Pacific Products, Inc. (1)	Broken Bow, OK
11	Plum Creek MDF, Inc. (1)	Columbia Falls, MT
12	Sacopan, Inc. (1)	Sacre-Coeur, Quebec
13	SierraPine, Ltd. (2)	Medford, OR; Rocklin, CA
14	Temple-Inland (1)	Mt. Jewett, PA
15	Uniboard Canada, Inc. (2)	La Bale, Quebec; Mont-Laurier, Quebec
16	Unilin US MDF (1)	Mt. Gilead, NC
17	West Fraser Mills Ltd. (2)	Quesnel, British Columbia; White Court, Alberta
18	Weyerhaeuser Co. (3)	Bennettsville, SC; Eugene, OR; Malvern, AR
Source: Composite Panel Association (Not Dated).		

c. Hardwood Plywood

Statistics compiled by the U.S. Department of Commerce report that hardwood veneer products accounted for nearly 25% of the industry's output in the early 1990's (Answers.com, Not Dated). In the late 1990's, North American shipments (i.e., production) of hardwood veneer products were worth approximately \$1 billion. The U.S. Department of Commerce reported that approximately 50% of the plywood and veneer output in the 1990's was mainly consumed in residential construction, and 25% was utilized in other lumber and wood products industries, while 11% was used in furniture and fixtures. The U.S. Census Bureau estimated that there were 332 facilities in the U.S. that made hardwood veneer and plywood in the late 1990's. Hardwood plywood production in 2000 was estimated to be 2.04 million m<sup>3</sup> (including core material such as softwood plywood and OSB), in 2000 these firms shipped \$3.3-billion worth of goods and

employed approximately 24,000 workers (Encyclopedia of American Industries, 2007).

In North America, Indiana, North Carolina, Wisconsin, and Michigan had the largest product shipments in this segment (Answers.com, Not Dated). One of the principal industry leaders in this category is Ply Gem Industries Inc., with 4,079 employees, followed by two Oregon, based companies; Roseburg Forest Products Co., with 3,975 employees and Columbia Forest Products Inc. had 3,500 employees.

In North America, the interest of hardwood plywood manufacturers are largely represented by the Hardwood Plywood and Veneer Association (HPVA), based in Reston, VA (Table VIII-3). Member companies of HPVA produce 90% of the HWPW stock panels and hardwood veneer manufactured in North America. The HPVA is an international trade association, currently representing more than 150 wood industry companies in the U.S., Canada, and abroad.

Table. VIII-3. Hardwood Plywood Facilities in North America		
No.	Company (No. Mills)	Mill(s)
1	Atlantic Veneer Corp. (1)	Beaufort, NC
2	Autumn House (1)	Granite Falls, NC
3	Besse Forest Products (1)	Matoon, WI
4	Birchland Plywood, Ltd (1)	Thessalon, Ontario
5	Buffalo Veneer & Plywood (1)	Buffalo, MN
6	Chesapeake Hardwood Prod. (1)	Chesapeake, VA
7	Columbia Forest Products (7)	Trumann, AR; Old Fort, NC; Klamath Falls, OR; Chatham, VA; Hearst, Ontario; St. Casimir, Quebec
8	Commonwealth Plywood Co. (1)	Ste-Therese, Ontario
9	Darlington Veneer Co., Inc. (1)	Darlington, SC
10	Duraply De Parral (1)	Parral, Chihuahua, Mexico
11	European Panel Products (1)	San Diego, CA
12	Florida Plywoods Inc (1)	Greenville, FL
13	G/L Veneer Co., Inc. (1)	Huntington Park, CA
14	General Veneer Manufacturing (1)	South Gate, CA
15	Howell Plywood Corp (1)	Dothan, AL
16	K & L Woodworking, Inc (1)	Reading, PA
17	Mt Baker Products, Inc. (1)	Bellingham, WA
18	Murphy Plywood Co. (1)	Eugene, OR
19	Navy Island Plywood (1)	West St. Paul, MN
20	Norbord Industries (2)	Toronto and Cochrane, Ontario

Table VIII-3. Continued		
No.	Company (No. Mills)	Mill(s)
21	Nova Wood lamination Inc. (1)	Kitchener, ON, Canada
22	Panoply Corp (1)	Lexington, TN
23	PanTim Wood Products, Inc. (1)	Portland, ME
24	Panel Source International, Inc. (1)	St. Albert, Alberta, Canada
25	Pavco Industries, Inc. (1)	Pascagoula, MS
26	Perfecta Plywood Ltd. (1)	St-Hyacinth, QC Canada
27	Pittsburgh Forest Products (2)	McMurray, PA; Toledo, OH
28	Pluswood (1)	Oshkosh, WI
29	Plywood Mfg. of California, Inc. (1)	Torrance, CA
30	Pro-Ply Custom Plywood, Inc. (1)	Mississauga, ON Canada
31	Roseburg Forest Products Co. (1)	Roseburg, OR
32	States Industries, Inc. (2)	Eugene, OR; Mocksville, NC
33	South West Panel Products (1)	Katy, TX
34	Timber Products Company (4)	Springfield, OR; Corinth, MS; Medford, OR; Grants Pass, OR
35	Veneer One Inc. (1)	Oceanside, NY
36	Vermont Plywood (1)	Hancock, VT
37	Western Panel Mfg., Inc. (1)	Eugene, OR
38	The Wood Gallery, Inc. (1)	Dallas, TX
39	Greenline Plywood Prod., Ltd. (1)	Stouffville, Ontario
<u>Source:</u> Hardwood Plywood and Veneer Association (2007)		

In the CARB 2003 Survey, responses were received from ten-mills regarding HWPW production volume (CARB, 2003). The range in reported annual production amounts was 300-thousand to 218-million ft<sup>2</sup>, where the median annual production of the ten-mills was 69-million ft<sup>2</sup>. For the HWPW cost analysis we classified the mills as either small, mid-size, or large manufacturers; in this case, small manufacturers were designated as mills that produced less than 25-million ft<sup>2</sup> (3%), mid-size manufacturers between 25- to 100-million ft<sup>2</sup> (44%), and large manufacturers more than 100-million ft<sup>2</sup> (53%). Unlike PB and MDF mills, which appear to be fairly substantial size fairly, small HWPW mills may be operated by 10- to 15-employees.

The extent of modification necessary to produce hardwood plywood that complies with the proposed Phase 1 and Phase 2 standards in 2009 to 2012 will largely depend on the age of the industry (mills), equipment being used, wood species, and type of plywood being made. Approximately 40 to 50 percent of the hardwood plywood products sold in California are produced by companies that already expended resources to upgrade their facilities in the past several years. A two-tiered structure has emerged that includes plants that are newer, larger, and operate at low-cost while there are many older, specialized, smaller, high-

cost plants that try to survive, however, it is not clear what portion of the industry is comprised by the latter.

## **2. Legal Mandates**

Government Code §11346.3 requires state agencies to assess the potential for adverse economic impacts on California businesses and individuals when proposing to adopt or amend any regulation, such as the proposed ATCM. The assessment must include an evaluation of the impact of the proposed regulation on jobs, business expansion, elimination, or creation, and the ability of California businesses to compete with comparable entities in other states. In addition, Government Code §11357 and guidelines adopted by the Department of Finance (DOF) require CARB and other state agencies to estimate the associated cost or savings to any local, state, or federal agency from the proposed ATCM. The agency proposing a regulation is also required to determine whether, as a result of the regulation, any cost to local agencies or school districts is reimbursable by the state.

Health & Safety Code §57005 further requires CARB to perform an economic impact analysis of submitted alternatives to a proposed regulation before the adoption of any major regulation. A “major regulation” is defined as a regulation that would potentially cost California businesses more than \$10-million per year.

## **3. Affected Businesses**

Any business that manufactures or markets HWPW, PB, or MDF for sale or supply, or finished goods containing those materials for sale or supply in California would potentially be affected by the proposed ATCM. This would also include businesses that supply or manufacture resins used in the aforementioned commodities and surface treatments. In this regard, the proposed ATCM is anticipated to directly and indirectly affect a wide range of businesses in California, the U.S., and other countries. The directly affected businesses include the following Standard Industrial Classification (SIC) codes (U.S. Census Bureau, 2003):

2435: Hardwood Veneer and Plywood Manufacturing, and  
2493: Medium Density Fiberboard and Particleboard Manufacturing.

Presently, the U.S. Census Bureau is revising the SIC coding system to the North American Industry Classification System (NAICS). In this system, “Wood Product Manufacturing” is assigned to NAICS code number 321, under which manufacturers of HWPW are assigned to category number 321211, and MDF and PB manufacturers to 321219.

To our knowledge, the major manufacturers of HWPW, PB, or MDF are member companies of the Composite Wood Council and/or Composite Panel Association.

The Composite Wood Council membership also includes panel and finished good/product distributors, home furnishing and cabinet manufacturers, equipment manufacturers, suppliers, secondary manufacturers (including laminators, cut-to-size operations, and component manufacturers), transporters, and trade magazines in California. The Composite Panel Association represents over 95% of the North American manufacturing capacity for PB, MDF, hardboard, and other compatible products (Composite Panel Association, 2007).

While manufacturers of HWPW, PB, or MDF are examples of directly impacted businesses, wood furniture and cabinet makers would be examples of indirectly impacted businesses. As the proposed ATCM will require downstream entities to purchase and use the Phase 1- and Phase 2-compliant HWPW, PB, or MDF in finished goods, compliance with the proposed ATCM will present different challenges to the various entities in the distribution chain from manufacturers to retailers.

There will not be an impact on any local government agency or school district because the proposed ATCM specifically excludes them from the fabricator definition and, therefore, the fabricator requirements.

#### **4. Ability to Comply with the ATCM**

##### **a. Potential Business Impact**

This portion of the economic impact analysis is based on a comparison of the return on owners' equity (ROE) for affected businesses before and after inclusion of the cost to comply with the proposed requirements. The data used in this analysis are obtained from publicly available sources, the 2003 CARB Survey, the Dun and Bradstreet financial data website, and the staff's cost analysis discussed later in this chapter.

##### **i. Affected Manufacturers**

The survey identifies 25 mills nationwide that potentially will be affected by the Phase 2 standards of the proposed ATCM. Only nine mills owned by three companies are located in California. Of the 25 mills, there are 10 that manufacture PB which are owned by eight companies. There are nine that manufacture MDF owned by three companies, and six that manufacture HWPW that are owned by six companies. Table VIII-4 provides a range of cost per plant for these mills by product type.

Table VIII-4. Cost per Plant by Type of Affected Product			
Product	Companies	Mills	Cost per Plant
PB	8	10	\$0.12 to 17.8 million
MDF	3	9	\$0 to 15.9 million
HWPW	6	6	\$0 to 6.6 million
Total	17	25	\$127 million

ii. Study Approach

This study covers 14 affected companies because three of the above companies manufacture both PB and MDF. The approach used in evaluating the potential economic impact is outlined as follows:

- Compliance cost was estimated for each of these businesses.
- Estimated cost was adjusted for federal and state taxes.
- The three-year average ROE was calculated, where data were available, for each of these businesses by averaging their ROEs for 2003 through 2005. ROE is calculated by dividing the net profit by the net worth. The adjusted cost was then subtracted from net profit data. The results were used to calculate an adjusted three-year average ROE. The adjusted ROE was then compared with the ROE before subtraction of the adjusted cost to determine the potential impact on profitability of the business. A reduction of more than 10% in profitability is considered to indicate a potential for significant adverse economic impacts.

The threshold value of 10% has been used consistently by CARB staff to determine impact severity. This threshold is consistent with the thresholds used by USEPA and others.

iii. Assumptions

Calculations of ROEs before and after subtraction of the adjusted compliance costs were based on the following assumptions:

- All affected businesses were subject to the highest federal and state corporate tax rates of 35% and 9.3%, respectively; and
- Affected businesses are not able to increase the prices of their products, nor can they lower their costs of doing business through short-term cost-cutting measures.

We understand that this last assumption is too conservative and it is unlikely to occur. This assumption is made to assess the severity of impacts using static measures of profit. According to USEPA (2004), plywood and reconstituted

wood products that are used in the construction industry have a price elasticity of demand ranging from -0.10 to -0.27. This implies that for every 10% change in the price of these products, the quantity demanded for these products would decline from 1 to 2.7%. In other words, the affected manufacturers have a great ability to pass on their compliance costs to consumers. Thus, it is likely that most manufacturers will be able to recover the bulk of compliance costs through higher prices for their wood products.

iv. Results

These businesses are affected by the proposed ATCM to the extent that the additional costs imposed by the proposed requirements would change their profitability. A detailed discussion and analysis of these costs is provided in the cost section of this report. According to the staff's cost analysis, the costs of manufacturing a 4' x 8' compliant wood panel board will range from about 3 to \$6. The Phase 2 standards of the proposed ATCM will affect about 1.2 billion ft<sup>2</sup> of wood panel board used in California, thereby imposing approximately 127 million in costs on composite wood manufacturers.

Using ROE to measure profitability, we found that the average ROE of affected businesses declined by about 12% as shown in Table VIII-5. This represents a significant change in the average profitability of these businesses if they absorbed the entire cost of compliance. However, as stated above, these businesses are most likely to be able to recover the bulk of the cost increase from consumers because of inelastic demand for their products. In such a case, the maximum price increase of a 4' x 8' compliant wood panel to consumers would range from approximately \$3.60 to \$7.20 if manufacturers are able to recover the entire compliance cost of the proposed ATCM.

Table VIII-5. Change in Return on Owner's Equity (ROEs) for Typical Manufacturers in the Composite Wood Products Industry <sup>1</sup>	
Product Manufactured	ΔROE
Particleboard	1.0%
Medium Density Fiberboard	1.1%
Hardwood Plywood	64.1%
Average	11.6%

(<sup>1</sup>) "Δ" = change; all ΔROEs shown are negative (i.e., shows a decline in profitability).

As shown in Table VIII-5, the projected change in profitability of typical businesses in composite wood industry varies widely. The predicted decline in profitability of these businesses ranged from a high of about 64% for a HWPW manufacturer to a low of 1.0% for a PB manufacturer. This variation in the

impact of the proposed ATCM can be attributed mainly to the following factors. First, some manufacturers incur higher costs due to the quantity of noncompliant wood products they manufacture or market. For instance, the estimated annual costs for affected businesses ranged from a high of about \$55 million to a low of about \$112,000. Second, some manufacturers operate multiple mills of different sizes, others operate only one mill. Finally, the performance of manufacturers may differ from year to year. Hence, the average 2003 through 2005 financial data used may not be representative of an average-year performance for some manufacturers.

The estimated changes to ROEs may be high for the following reasons. First, annual costs of compliance are estimated using, in part, the current prices of raw materials. Raw material prices usually tend to fall as higher demand for these materials induces economy of scale production in the long run. Second, as stated above affected manufacturers probably would not absorb all of the increase in their costs of doing business. They would be able to pass some of the cost on to consumers in the form of higher prices. Also, they might be able to improve their operational efficiency, thus reducing their costs.

b. Potential Impact on Employment

The proposed ATCM is not expected to cause a noticeable change in California employment and payroll. According to the 2004 U.S. Census Bureau (U.S. Census Bureau, 2006a; 2006b), California employment in the composite wood product industry (NAICS 321211/SIC 2435 and NAICS 321219/2493, which includes establishments engaged in manufacturing hardwood veneer and plywood, and reconstituted wood products) was 1,449 in 2004, or about 3.5% of the national employment in the industry. This represents about 0.1% of the total manufacturing jobs in California in 2004. These employees working in 38 establishments generated about \$49 million in payroll (Table VIII-6), accounting for less than 0.1% of total California manufacturing payroll in 2004. Six establishments had 100 employees or more; the other 32 had less than 100 employees each.

Table VIII-6. Establishments, Employees, and Payroll by Industry				
NAICS	SIC	Establishments	Employees	Annual Payroll
321211	2435	18	570	\$13,794,000
321219	2493	20	879	\$34,971,000
Total		38	1,449	\$48,765,000

The employment in the composite wood products industry accounts for a small portion of the California economy. The employment in the industry is unlikely to change significantly as a result of the proposed ATCM. This is because demand for affected products is price inelastic; implying that affected manufacturers or

marketers would be able to pass on the bulk of the cost increase to consumers in terms of higher prices for their products. In addition, strict enforcement of the proposed ATCM may enable domestic manufacturers to expand their California market share. Overseas manufacturers that produce low cost high emitting products are likely to lose some of their current price advantages over domestic manufacturers when the proposed ATCM goes into effect. Thus, most domestic manufacturers are likely to maintain their current profitability and as a result, no noticeable change is expected in their employment.

## **B. Cost of Compliance**

### **1. Price Trends**

In the U.S., the housing sector largely determines the demand for wood products (lumber and composite panels) (U.S. Department of Agriculture, Not Dated). It is estimated that over 55% of the engineered wood products (e.g., PB, MDF, plywood, oriented strand board) manufactured in the U.S. is sold to residential house builders, and an additional 18% to commercial and industrial buildings (Global Wood Trade Network, 2005). The furniture industry consumes a 22% share, mostly PB and MDF. Only 4% is exported (estimated valued = \$1.2-billion), with nearly 50% of exports sold to Canada.

#### **a. Particleboard**

From 1995 to 2005, unit prices of industrial PB (\$/thousand square feet (\$/MSF)) ranged from \$250 in 2003 to \$328 in 2004 (Table VIII-7) (Composite Panel Association, 2006). Comparable unit prices were reported in Random Lengths (2006) for Eastern PB, where prices ranged from \$214 to \$291. Relative to PB production, the decrease in unit price coincides with a drop in production volume in 2001, just prior to the start of a strong upturn in housing starts in 2003 (Random Lengths, 2006). As the number of housing starts remained high in 2004 and 2005, there was an increase in PB production to meet demand, and unit prices remained above \$300 per MSF. Using housing starts as an indicator of wood product demand in the housing sector, the fluctuations in the unit price of PB from 2002 to 2005 can be explained, in part, by the sufficiency of PB supplies (and lower prices) in 2002 and 2003, followed by temporary shortages leading to increased production and higher costs in 2004 and 2005.

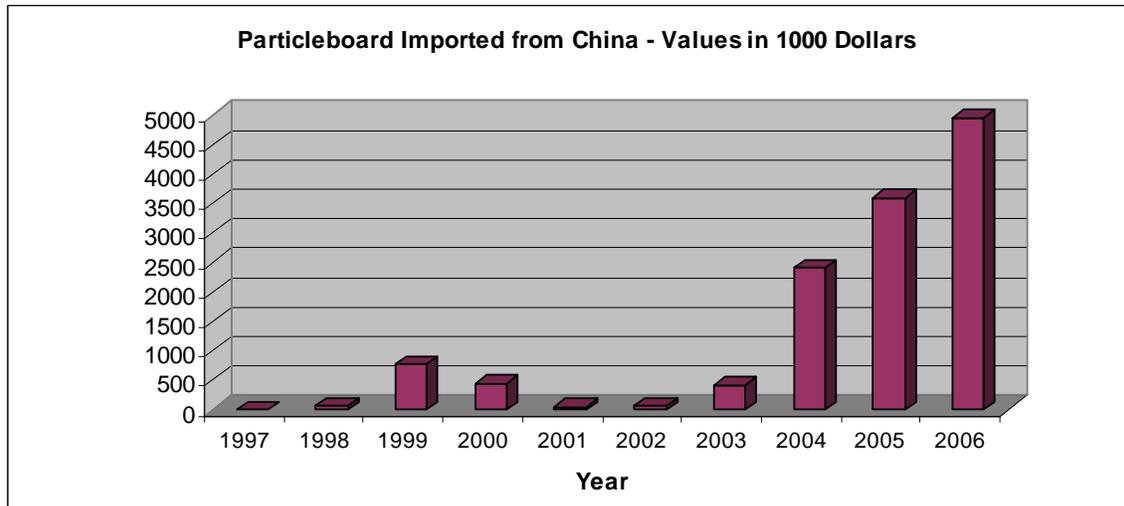
Table VIII-7. Unit Cost of Industrial Particleboard: 1995-2005<sup>1</sup>

Year	----- Industrial Particleboard (\$/MSF) -----		Production (MSF)
	Composite Panel Association	Random Lengths -- East	
1995	306	289	4,199,735
1996	287	285	4,367,662
1997	288	274	5,553,339
1998	274	269	5,836,159
1999	297	282	6,148,748
2000	321	286	6,113,097
2001	279	250	5,582,154
2002	263	214	6,016,915
2003	250	222	5,585,105
2004	328	291	5,851,270
2005	311	283	5,626,080
Mean	291	268	-----

<sup>(1)</sup> Source: Composite Panel Association (2006); Random Lengths (2006a). “\$/MSF” = Dollars per million square feet. Data for industrial particleboard are estimated on a ¾” basis.

Some of the demand for PB during 2004 and 2005 may have been met by increasing the amount of imports or by reducing exports (Figure VIII-1). In 2002, total U.S. imports of PB from China were valued at approximately \$56,000 (U.S. Department of Agriculture, Not Dated (a)). Over the ensuing four-years, the value of Chinese imports has risen nearly 100-fold to approximately \$5-million. At a unit price of \$300 per MSF, the represents about 16,500 MSF, less than 0.5% of total U.S. production in 2005 (Composite Panel Association, 2006).

Figure VIII-1. Value (\$) of U.S. Imports of Particleboard from China: 1997 to 2006<sup>1</sup>



<sup>(1)</sup> Source: U.S. Department of Agriculture (Not Dated (a)).

b. Medium Density Fiberboard

In 1995 to 2005, unit prices (\$/MSF) of MDF ranged from \$340 in 1999 to \$442 per MSF in 1995; the 10-year mean was \$380 per MSF (Table VIII-8) (Composite Panel Association, 2006). Similar findings were reported by Random Lengths (2006a) for western MDF; unit prices ranged from \$337 to \$416 per MSF. In contrast to PB, MDF production has increased steadily over this period from 1.1-million MSF in 1995 to 2.6-million MSF in 2005. However, similar to PB, unit prices rose substantially in 2004 and 2005, possibly due to an increased demand for MDF in the housing sector.

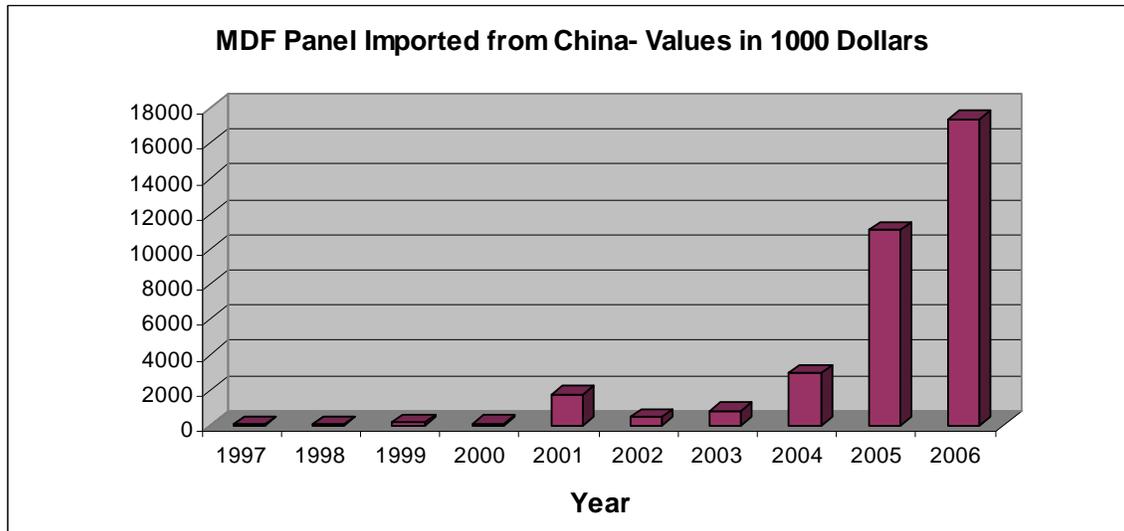
Table VIII-8. Unit Cost of Medium Density Fiberboard: 1995-2005<sup>1</sup>

Year	----- Medium Density Fiberboard (\$/MSF) -----		Production (MSF)
	Composite Panel Association	Random Lengths -- West	
1995	442	-----	1,106,827
1996	387	411	1,200,700
1997	350	362	1,715,842
1998	337	342	1,900,486
1999	340	344	2,199,102
2000	366	358	2,193,398
2001	365	369	2,125,431
2002	389	366	2,386,843
2003	373	337	2,284,945
2004	399	415	2,554,629
2005	435	416	2,647,575
Mean	380	372	-----

<sup>(1)</sup> Source: Composite Panel Association (2006); Random Lengths (2006a). “\$/MSF” = Dollars per million square feet. Data for medium density fiberboard are estimated on a  $\frac{3}{4}$ ” basis.

Imports of MDF from China, as for PB, have risen substantially since the late 1990’s (Figure VIII-2). In 2002, total U.S. imports from China were valued at approximately \$500,000 and in 2006, were in excess of \$17-million (U.S. Department of Agriculture, Not Dated (a)). At a unit price of \$400 per MSF, the present amount of imported MDF from China represents approximately 43,500 MSF or 1 to 2% of total U.S. production.

Figure VIII-2. Value (\$) of U.S. Imports of Medium Density Fiberboard from China: 1997 to 2006<sup>1</sup>



<sup>(1)</sup> Source: U.S. Department of Agriculture (Not Dated).

c. Hardwood Plywood

For HWPW, we were not able to find historical unit price data for panels. However, as shown in Table VIII-9, we found that wholesale panel prices vary considerably depending on the type of face species and core used in the panel.

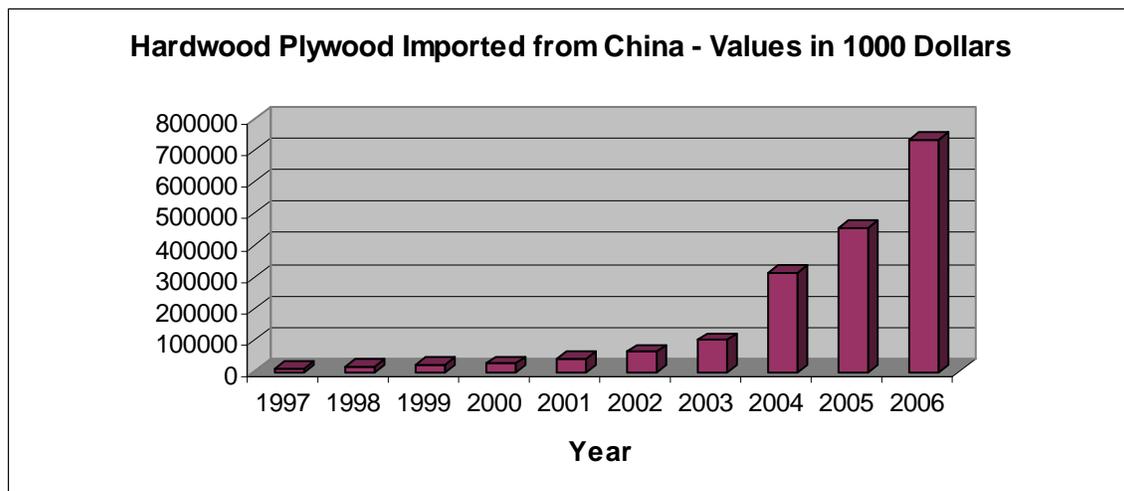
Face Species	Core	Price per MSF	Price per Piece
White Maple	Particleboard	\$375	\$12
Nat. Birch	Veneer	\$312	\$10
Cherry	Particleboard	\$375	\$12
Hickory	Veneer	\$469	\$15
White Maple	Veneer	\$469	\$15
Luxcell	Veneer	\$469	\$15
White Birch	Veneer	\$500	\$16
Red Oak	Veneer	\$500	\$16
Red Oak	Particleboard	\$375	\$12

<sup>(1)</sup> Source: Pittsburgh Forest Products Company (2007).

Currently, the HWPW industry has been experiencing strong competition from foreign producers. Imports of veneer, plywood and engineered wood products exceed exports by a wide margin (Global Wood, 2005). In 2004, imported products were valued at approximately \$9-billion, which represents nearly 25% of domestic demand. The growth in 2004 was estimated to be 51%, in spite of the weakening U.S. dollar. The U.S. trade deficit in veneer, plywood, and engineered wood products is \$7.8-billion.

Imports of HWPW from China, as for PB and MDF, have risen substantially since the late 1990's (Figure VIII-3). In 2002, total U.S. imports from China were valued at approximately \$64-million and in 2006, were in excess of \$730-million (U.S. Department of Agriculture, Not Dated (a)).

Figure VIII-3. Value (\$) of U.S. Imports of Hardwood Plywood from China: 1997 to 2006<sup>1</sup>



<sup>(1)</sup> Source: U.S. Department of Agriculture (Not Dated (a)).

According to Wood Based Panels International (2006), the major plywood suppliers to the U.S. are Brazil, with 1.6-million m<sup>3</sup> (30.4% market share), China with 1.3 million m<sup>3</sup> (24.2%), and Canada with 700,000 m<sup>3</sup> in 2005 (13.4%). Brazil, China, and Canada account for a combined market share of approximately 67%.

## 2. Effect of Imports

The U.S. is the world's leading importer of wood products (\$23.3 billion), followed by the EU-25 (\$13.2-billion), and Japan (\$11.8-billion) (Global Trade Atlas, Not Dated), where in 2004, the major U.S. suppliers were Canada (61%), China, and Brazil. The market leader for engineered wood products in the U.S. is Weyerhaeuser (10% market share); Georgia-Pacific, Boise Cascade, and

Louisiana-Pacific are the next largest U.S. producers, and the combined U.S. market share of these four companies is approximately 30% (Global Wood Trade Network, 2005).

As the demand for low-cost composite wood products continues to remain high in the U.S., the demand is increasingly being met by imports, due in part to higher costs for labor, energy, raw materials, and environmental compliance in the U.S. In addition to panel manufacturers, furniture companies in the U.S., Europe, and Mexico have also commented about the increasing amount of furniture coming from China, where labor costs are lower (i.e., Chinese furniture exports in 1999 and 2005 were \$5-billion and \$22-billion, respectively) (Bowersheim, Not dated). Although Canada is the leading source of imported wood products to the U.S., products from China are increasing in market share and may continue to rise in light of reported plans for production line improvements (U.S. Department of Agriculture, Not Dated (b)). Presently, a typical Chinese production line is relatively small, producing less than 50,000 m<sup>3</sup> per year vs. 170,000 m<sup>3</sup> per year in other countries (i.e., 50,000 m<sup>3</sup> ≈ 29,000 MSF). While China has made regular purchases of four to six presses each year, it was reported that the Shanghai Wood-based Panel Machinery Co., Ltd. has recently developed a continuous plat press with an annual output capacity of 200,000 m<sup>3</sup> that may be put into production beginning in 2007 (Global Wood Trade Network, 2007).

### **3. Factors to Consider for Regulatory Compliance**

Currently, the major centers of composite panel manufacturing in the U.S. are located in the Pacific Northwest, Northeast, and Southeast (USEPA, 2002). For the most part, large manufacturers with customers throughout the country operate mills in each of these regions in order to deliver their products in a timely and cost-competitive manner. It is estimated that California consumes roughly 11% of the composite wood products manufactured in the U.S., and thus, manufacturers could choose whether or not to supply products to meet this sector of the U.S. Presumably, in consideration of the present way composite wood products are supplied to customers, the major portion of products for the California market would be supplied by mills in the Pacific Northwest. However, as a major portion of the U.S. furniture and cabinet industry is located on the eastern seaboard, some portion of manufacturers may choose to produce CARB-compliant products for finished goods that will be sold to California.

Since the proposed Phase 1 and Phase 2 standards are based on emissions performance, several resin systems could be used. If a company determines that major upgrades are needed to produce CARB-compliant products at one of their mills, they would have the option to make “49-state” products at that mill for sale in other states or countries. Given the absence of HCHO emission standards for wood products of equal stringency to the proposed ATCM when it is fully implemented, in other states, Europe, and selected parts of Asia,

manufacturers with multiple mills would not be required to convert their entire operation to producing CARB-compliant composite wood products.

In the following subsections, the projected increase in the cost of PB, MDF, and HWPW manufactured to comply with proposed Phase 2 standard is described. Understanding the incremental increase in cost on a panel-basis is fundamental to evaluating costs downstream, in that the costs of storing and redistributing the products are passed on from one level to the next. The analysis in this section serves to establish the incremental production cost to manufacturers, as a basis for assessing downstream cost to consumers.

#### **4. Particleboard: Estimated Increase in Panel Cost**

The five main steps in PB manufacturing are: (1) preparation of the furnish (i.e., wood particles), (2) resin application, (3) mat formation, (4) hot pressing, and (5) finishing. The furnish is prepared by refining logs and other raw materials into small particles, and drying them to achieve a moisture content of 2 to 7% (Cognard, 2005). To control HCHO emissions, it is projected that selected manufacturers using PF resins may need to upgrade or purchase new dryers to more precisely control the moisture contents of the PB furnish that they use to make panels compliant with the proposed Phase 1 and Phase 2 standards. To optimize their drying operations, these manufacturers may incur a one-time capital investment for a new dryer. Depending on the size and energy rating of the new dryer, energy costs may increase, but some of these costs may be offset by savings due to more precise resin use.

During resin application, resin is mixed with the furnish. In PB made with a UF resin, the resin accounts for 5 to 12% of the total weight of the panel depending on the size of the wood particles and the required properties of the panel (e.g., moisture resistance) (Cognard, 2005; Goldboard, 2000). Projected cost impacts during resin application will depend on the type of resin that manufacturers choose to produce panels compliant with the proposed Phase 1 and Phase 2 standards, as the use of a new resin may require changes in mixing or application equipment, as well as the cost of the new additives, if any.

After a UF resin is thoroughly mixed with the furnish, the mixture is cold-pressed to form a mat, then hot-pressed at cure temperatures ranging from 130 to 150 °C (Cognard, 2005). In comparison, PB made with PF resin requires hot-pressing at temperatures ranging from 180 to 230 °C (Pizzi, 1994). As greater energy costs will be incurred from the use of higher hot-press temperatures and longer press times, the increase cost per panel is expected to range on a case-by-case basis. The range of changes that a manufacturer chooses to make will determine the extent of the cost increase that they incur.

In the finishing process, PB panels are trimmed, cut, and sanded to produce panels of a desired thickness. Staff expects that any changes in the costs associated with the finishing process would be insignificant.

To maintain a competitive board price, optimization of the manufacturing process may provide cost savings to varying degrees. For example, optimizing resin distribution and application systems could reduce resin waste, and lower manufacturing costs as well as surface HCHO emissions from the board.

a. Drop-in Approach: Modified UF or Alternate Resin

In this subsection, the estimated cost of manufacturing a PB panel with a modified or alternate resin system, which does not require an upgrade to the existing equipment in a mill, is discussed. It is projected that to manufacture PB that complies with the proposed Phase 1 and Phase 2 standards, manufacturers will need to modify their existing UF resins or use an alternative resin system, which could have a measurable impact on the resin cost portion (30%) of the total cost of manufacturing a PB panel (Table VIII-10).

The cost of manufacturing PB can be apportioned into six categories: adhesive, energy, labor, wax, wood, and miscellaneous costs (Table VIII-10). Among the six categories, the cost of the adhesive and wood amounts to over 50% of the total cost of manufacturing a panel. In future years, the cost of wood particles may rise significantly due to the shortage of harvestable forests in the U.S. and the inability to produce PB entirely from furnish made with urban wood waste. Moreover, the future cost of petroleum-based adhesive components (e.g., HCHO) is uncertain given the volatility in supply and demand that has occurred over the last 10-years.

Table VIII-10. Breakdown of Costs in Particleboard Manufacturing <sup>1</sup>	
Category	Percent (%) of Panel Cost
Adhesive	30
Electricity	9
Labor	19
Wax	3
Wood Particles	24
Miscellaneous	15
<sup>(1)</sup> Source: Industry Canada (2005a; 2005b).	

Selected measures of the cost of PB and an estimate of the cost for the resin used to bind the furnish in PB ranging in thickness from 3/8" to 3/4" is presented in

Table VIII-11. Over this range of PB thickness, the present cost of the UF resin used to manufacture a PB panel ranges from \$2.74 to \$3.57.

Table VIII-11. Estimated Cost of UF Resin in Particleboard of Varying Thickness <sup>1</sup>				
Measure of Cost	----- Board Thickness (Inches) -----			
	3/8"	1/2"	5/8"	3/4"
1,000 ft <sup>2</sup>	\$286	\$299	\$333	\$372
4' x 8' Panel	\$9.15	\$9.57	\$10.66	\$11.90
Estimated Resin Cost	\$2.74	\$2.81	\$3.20	\$3.57

(<sup>1</sup>) Sources: Random Lengths (2006b); Industry Canada (2005a; 2005b).

Urea-formaldehyde (UF) is the most commonly used resin for manufacturing interior grade PB in the U.S., largely because of its relatively fast curing speed and low cost. As the cost of the resin used to bind the wood particles in PB typically accounts for approximately 30% of the price of a PB panel (Industry Canada, 2005b), assuming that manufacturers may choose to use an alternate resin system to lower their HCHO emissions, our analyses indicate that the most likely alternates would include MF, MUF, PUF, pMDI, and PF. As the prices for these resins are higher than for UF resin, the cost of a PB panel compliant with the proposed Phase 1 or Phase 2 standards is expected to increase (Table VIII-12). In calculating a “final cost,” factors such as press conditions (e.g., press temperature, curing rate and application rate) and the use of additives (e.g., extenders, hardeners, scavengers), which may increase or decrease the final cost, were considered.

Efficient application of extenders may reduce overall resin costs by up to 10% (Marutzky, 1989; Frihart, 2005) – extenders or fillers (e.g, walnut shell flour), can be added to resins to reduce adhesive cost by limiting the amount of resin over-penetration into wood particles. Hardeners or curing agents can be added to a resin to accelerate the hardening process, and could increase total production rates by up to 10%. Scavengers may also be added to reduce HCHO emissions during or after production. Commonly added scavengers include urea alone, or in combination with ammonium chloride or with organic amines. Panel manufacturers report that the application of scavengers could increase board prices by 1 to 5%.

Table VIII-12. Estimated Price Increase in Particleboard Made to Comply with the Phase 2 Standard with an Alternate Resin<sup>1</sup>

Resin Type	Cost (\$ lbs <sup>-1</sup> )	Cure Temp.	Cure Rate	HCHO (ppm)	Price Increase (%)
UF	0.24-0.27	NA	NA	0.3	NA
MF	0.72-0.81	Higher	Slower	< 0.09	60 to 70
MUF (<12%)	0.31-0.46	Higher	Slower	< 0.09	10 to 30
MUF (>12%)	0.48-0.68	Higher	Slower	< 0.09	30 to 55
MUF + Catcher	0.24-0.27	Similar	Similar	< 0.09	< 5
PF	0.48-0.68	Higher	Slower	< 0.09	30 to 55
pMDI	0.96-1.35	Lower	Slower	Trace	90 to 140

<sup>(1)</sup> "Cure Temp." = cure temperature; "ppm" = parts per million; "NA" = not available; "UF" = urea-formaldehyde; "MF" = melamine-formaldehyde; "MUF" = melamine-UF; "PF" = phenol-formaldehyde; "pMDI" = polymeric diphenylmethane diisocyanate. Cure rate and temperature are relative to production conditions for manufacturing particleboard (PB) with a UF resin. Values for "Price Increase" are relative to the cost of PB made with a UF resin; effects of cure temperature and rate were not considered. Resin costs are based on price information supplied at public workshops or in stakeholder meetings.

Melamine-formaldehyde (MF) resin is presently used as an adhesive in exterior and semi-exterior grade plywood and PB, decorative laminates, paper treating and coating (Pizzi, 1994; Youngquist, 1999). As an alternative to UF resin, the use of MF resin may be cost-prohibitive in the 2010 to 2012 timeframe. It is estimated that PB made with a MF resin that complies with the proposed Phase 2 standard could cost up to 60 to 70% more than PB made with UF resin.

Melamine Urea-formaldehyde (MUF) resin has been shown to improve the moisture resistance of PB while lowering surface HCHO emissions. Typically, a MUF resin with a melamine content of 12% or less is used to lower thickness swell as well as surface HCHO emissions. Conceivably, the use of a MUF resin with lower melamine contents could result in PB production costs comparable to the use of a UF resin. According to one major resin manufacturer, a 1% increase in the melamine content of a resin raises the cost of the resin by as much as \$25 to \$30 per ton (1.2 to 1.5¢ per pound). While the cost of manufacturing PB with a MUF resin is expected to be higher, its superior moisture resistance may allow it to command a higher price than PB made with a UF resin having lesser moisture resistance properties, thus moderating the extent of the overall impact of the projected cost increase (10 to 30%). Akzo Nobel (2005) has developed a "catcher" which has been used in Europe to produce panels meeting the E1 standard, and has the potential to be used as an additive that would minimally increase the manufacturing cost of PB made with a UF resin.

Phenol-formaldehyde (PF) resin is principally used in the manufacture of exterior-grade plywood and PB, where superior water resistance is required. Blends of PF resins with resorcinol (i.e., PRF resins) are known to provide advantages insofar as lower cure temperature (Frihart, 2005). However, resorcinol is very expensive to use, and PRF resins would not be a cost-competitive alternative to UF resin. At present, it is projected that at resin application rates currently used to manufacture exterior-grade PB, the cost of a PB panel compliant with the proposed Phase 2 standard would be 30 to 55% higher due to higher resin costs and higher press temperatures. Further resin development to allow faster cure speeds could significantly lower production costs.

Polymeric diphenylmethane diisocyanate (pMDI) resin has a low viscosity (Marutzky, 1989), which typically is mixed with a releasing agent to prevent panels from sticking to metal surfaces during hot pressing. Although pMDI resin is more expensive than UF resin (Table VIII-9), there are production cost-savings that partially offset the higher resin cost, such as the ability to use furnish with a higher moisture content and lower resin spread rate (Zheng, 2002). Analogous to MUF resins, higher prices could be afforded to PB made with pMDI owing to its superior water resistance relative to PB made with a UF resin. Further cost-savings may also be achieved through the use of agricultural residues, such as wheat or rice straw in place of wood particles. At the plant-level, conversion of existing UF or PF facilities to pMDI should not require substantial manufacturing process-related capital investment (Goldboard, 2000).

Despite its high cost, Osman et al. (1994) reported making PB with a phenol-urea-formaldehyde (PUF) resin to which they added MDI alone, or in combination with urea. Of the three components, the cost of MDI (approximately \$2,200 per ton) was approximately twice that of PUF (approximately \$1,000 per ton) and ten-times more than urea (approximately \$200 per ton). These workers reported making PB with PUF-MDI-urea resins that were comparable in cost and internal bond strength to PB made with the PUF resin.

b. Plant Upgrade: New Equipment

Sellers (2001) reported on a suite of technologies being developed to improve productivity in the panel manufacturing process. The list included:

- Radio-frequency curing – to provide more precise control over adhesive-related processes, increase production, and uniformity of curing;
- Steam injection – to accelerate cure rates for pMDI and PF resins;
- Foam extruders – to reduce adhesive use, trim loss, and clean-up;
- Continuous presses – to increase production and control product surface roughness over that achieved by batch platen presses; and
- Resin additives to reduce tool wear.

In discussions with industry representatives, the cost of equipment replacement is a multi-million dollar undertaking, in that equipment such as presses or dryers have \$1-million or more price tags. As such, should a manufacturer elect to upgrade a plant to produce CARB-compliant products, it would likely involve an investment of \$200,000 to \$300,000 per year for ten or more years. Given the amount that it would cost to upgrade a plant, manufacturers would need to be reasonably certain of being able to recover their cost of investment. As they would have the option of producing products for markets other than California, it is not likely that manufacturers will make a major investment of this kind. Thus, in our view, unless manufacturers can produce CARB-compliant PB with “drop-in” technology, it is more likely that the plant will be dedicated to the production of “49-state” wood products.

c. Small Producers

Based on the CARB 2003 Survey, a small PB producer manufactures less than 110-million ft<sup>2</sup>, and would be operated by less than 100-employees. For this size of facility, in addition to higher resin costs, consideration must also be given to potential cost increases due to quality control testing and documenting chain-of-custody. If the producer is already a member of the Composite Panel Association or the Hardwood Plywood & Veneer Association, no additional costs may be anticipated for quality control testing and only minimal increases would be projected for labeling and chain-of-custody related activities. Likewise, compliance testing is tied to production volume, and therefore, smaller producers would conduct fewer tests over time than large producers, since they produce less product.

**5. Medium Density Fiberboard: Estimated Increase in Panel Cost**

In 2003, MDF production was 2.7-million m<sup>3</sup> in the U.S., where it is primarily used in the manufacture of furniture, shelving, molding, and kitchen cabinets (Composite Panel Association, 2006; Howard, 2005). Manufacturing processes for MDF are similar to that for PB, except that additional processing is required to prepare the fibers in the MDF furnish.

a. Drop-in Approach: Modified Urea-formaldehyde or Alternate Resin

The most promising alternative resins for making MDF that complies with the proposed Phase 1 and Phase 2 standards are similar to those for PB (Table VIII-12). For MDF, the cost of resin typically accounts for 27% of the cost of a panel (Industry Canada, 2005a). Estimates of the cost of resin in MDF of varying thickness are shown in Table VIII-13. For the most common thicknesses, the estimated cost of UF resin alone ranges from \$3 to \$4 per panel.

Table VIII-13. Estimated Cost of Urea-formaldehyde (UF) Resin in Medium Density Fiberboard (MDF) of Varying Thickness <sup>1</sup>				
Measure of Cost	----- Board Thickness -----			
	3/8"	1/2"	5/8"	3/4"
1,000 ft <sup>2</sup>	\$309	\$344	\$402	\$454
4' x 8' Panel	\$9.89	\$11.01	\$12.86	\$14.53
Estimated Resin Cost	\$2.67	\$2.97	\$3.48	\$3.92

(<sup>1</sup>) Source: Random Lengths (2006b). Estimated resin cost is based on the resin accounting for 27% of the cost of a MDF panel.

The estimated price increases for MDF made with an alternate resin are slightly less on a percentage basis than for PB. The most promising option at this time appears to be the addition of melamine to a UF resin (i.e., MUF), which could raise the price of a panel by 10 to 50% (Table VIII-14). While some manufacturers presently produce MDF with pMDI for specialty applications, unless the cost of the furnish material can be decreased significantly (e.g., fibers from rice straw instead of wood), the use of pMDI represents a higher cost option.

Table VIII-14. Estimated Price Increase in Medium Density Fiberboard Made to Comply with the Phase 2 Standard with an Alternate Resin <sup>1</sup>					
Resin Type	Cost (\$/lbs)	Cure Temp.	Cure Rate	HCHO (ppm)	Price Increase (%)
UF	0.24-0.27	NA	NA	0.3	NA
MF	0.72-0.81	Higher	Slower	<0.08	55 to 65
MUF (<12%)	0.31-0.46	Higher	Slower	<0.08	10 to 25
MUF (>12%)	0.48-0.68	Higher	Slower	<0.08	30 to 50
pMDI	0.96-1.35	Lower	Slower	Trace	80 to 125

(<sup>1</sup>) "Cure Temp." = cure temperature; "ppm" = parts per million; "NA" = not available; "UF" = urea-formaldehyde; "MF" = melamine-formaldehyde; "MUF" = melamine-UF; "pMDI" = polymeric diphenylmethane diisocyanate. Cure rate and temperature are relative to production conditions for manufacturing medium density fiberboard (MDF) with a UF resin. Values for "Price Increase" are relative to the cost of MDF made with a UF resin; effects of cure temperature and rate were not considered. Resin costs are based on price information supplied at public workshops or in stakeholder meetings.

b. Plant Upgrade: New Equipment

As noted for PB, the cost of equipment replacement is a multi-million dollar undertaking, where presses or dryers cost \$1-million a piece or more. As such, if a manufacturer chooses to upgrade a plant to produce CARB-compliant MDF, it could entail an investment of \$200,000 to \$300,000 per year for ten or more years. Given the cost to upgrade a plant, it is not likely that manufacturers will make a major investment of this kind, especially since they have the option to produce MDF for customers outside of California. Thus, in our view, unless manufacturers can produce CARB-compliant MDF with “drop-in” technology, it is more likely that a plant will be dedicated to the production of “non-California” wood products.

c. Small Producers

Based on the CARB 2003 Survey, a small MDF producer manufactures less than 100-million ft<sup>2</sup>, and would be operated by less than 100-employees. For this size of facility, in addition to higher resin costs, consideration must also be given to potential cost increases due to quality control testing and documenting chain-of-custody. If the producer is a member of the Composite Panel Association, no additional costs would be anticipated for quality control testing and only minimal increases would be projected for labeling and chain-of-custody related activities.

**6. Hardwood Plywood (HWPW): Estimated Increase in Panel Cost**

Plywood is made out of wood veneers and an inner core, where the core may be a wood veneer, lumber, PB, MDF, or a combination of materials. In 2003, HWPW production in the U.S. was estimated to be 1.9-million m<sup>3</sup> (Howard, 2005). The primary uses of HWPW are for interior wall panels, furniture, flooring, and cabinets.

a. Drop-in Approach: Modified Urea-formaldehyde or Alternate Resin

In a plywood panel, the cost of the resin is estimated to be about 5% of the total cost of the panel (Industry Canada, 2005b). In comparison, the cost of the resin accounts for 30% or 27% of the cost of a PB or MDF panel, respectively. For HWPW, the wood components (i.e., veneer and core materials) account for 50% or more of the cost the panel. Depending on the species and cut grade of the veneer, prices may range from \$0.89 to \$8.99 per ft<sup>2</sup> for selected oak veneers (Oakwood Veneer Company, 2006a, 2006b). For this price range, a 4' x 8' panel would cost \$29 to \$288. To control costs, some HWPW manufacturers import lower-cost cores from overseas suppliers. Depending on panel thickness, the cost of the UF resin in a panel can be approximately \$2 (Table VIII-15).

Table VIII-15. Estimated Cost of the Urea-formaldehyde (UF) Resin in Hardwood Plywood of Varying Board Thickness <sup>1</sup>				
Measure of Cost	----- Board Thickness (Inches) -----			
	1/2" Birch	3/4" Birch	3/4" Oak	3/4" Maple
4' x 8' Panel	\$33.95	\$39.99	\$42.99	\$38.00
Estimated Resin Cost	\$1.70	\$2.00	\$2.15	\$1.90

(<sup>1</sup>) Sources: Home Depot (2006); Industry Canada (2005b).

The estimated price increases for HWPW made with an alternate resin are considerably less on a percentage basis than for PB and MDF, due to the lower amount of resin used to manufacture HWPW. While the use of proprietary soy or "MUF + Catcher" resins are essentially cost-neutral, use of PVA or a PVA/soy resins could raise the price of a panel by 10 to 30% (Table VIII-16).

Table VIII-16. Estimated Price Increases in Hardwood Plywood Made with Alternate Resins <sup>1</sup>					
Resin Type	Cost (\$ lbs <sup>-1</sup> )	Cure Temp.	Cure Rate	HCHO (ppm)	Price Increase (%)
UF	0.24-0.27	NA	NA	0.3	NA
MUF + Catcher	0.24-0.27	Similar	Similar	<0.08	< 5%
PVA	0.55-1.50	Lower	Shorter	<0.05	10 to 30
Soy	0.24-0.27	Similar	Similar	<0.05	< 5%
PVA/Soy	0.72-0.81	Similar	Similar	<0.05	10 to 15

(<sup>1</sup>) "Cure Temp." = cure temperature; "ppm" = parts per million; "NA" = not available; "UF" = urea-formaldehyde; "MUF" = melamine-UF; "PVA" = polyvinyl acetate. Cure rate and temperature are relative to production conditions for manufacturing hardwood plywood with a UF resin. Values for "Price Increase" are relative to the cost of hardwood plywood made with a UF resin; effects of cure temperature and rate were not considered. Resin costs are based on price information supplied at public workshops or in stakeholder meetings.

Westcott and Frihart (2004) developed a soy-PF resin that could be a candidate system for producing HWPW that complies with the proposed Phase 1 and Phase 2 standards. In trials on oriented strandboard, these workers found that adding soy flour, at roughly 25% the cost of phenol, could reduce unit resin cost by 40 to 60%, at soy:phenol weight ratios of 1 and 3.4, respectively. While this is data on resin use in oriented strandboard, they postulate that results for plywood could be similar.

b. Plant Upgrade: New Equipment

For HWPW, the candidate resins that would likely be used to manufacture panels compliant with the Proposed Phase 1 and Phase 2 standards would not require new equipment for use. For example, several existing facilities that currently use urea formaldehyde resins also make HWPW with PVA resin in response to requests for “green building” compliant materials. In addition to the higher cost of PVA vs. UF resin, there are costs associated with cleaning the presses after using PVA that must be performed before returning to UF resin production. As such, if manufacturers produced only PVA-bonded HWPW, these cleaning costs would not be a consideration. In our view, manufacturers can produce CARB-compliant HWPW with “drop-in” technology, it is more a matter of whether they will choose to produce HWPW for California or not.

c. Small producers

While industry representatives have stated that there are 19-mills in the U.S., based on the CARB 2003 Survey, some of the smaller HWPW producers manufacture less than 1-million ft<sup>2</sup>, and would be operated by less than 20 employees. For this size of facility, in addition to higher resin costs, consideration must also be given to potential cost increases due to quality control testing if they continue to use UF resin and documenting chain-of-custody. If the producer is a member of the Hardwood Plywood & Veneer Association, the costs that would be anticipated for quality control testing, labeling, and chain-of-custody related activities may be less.

**C. Cost to the Composite Wood Manufacturing Industry**

**1. Calculation of Total Cost to the Industry**

There are about 1,500 companies in the American engineered wood products industry, employing over 120,000 workers. Their combined production value stood at an estimated \$29.5 billion in 2004. This compares to a value of \$21.3 billion at the beginning of this century. The increase of 38.5% is partially due to higher prices. However, if we exclude the impact of inflation, the growth between 2000 and 2004 is still 30.2% (Global Wood Trade Network, 2005).

a. Hardwood Plywood (HWPW)

Presently, about 40% of HWPW produced for California complies with the proposed Phase 1 and Phase 2 standards (Columbia Forest Products, 2006). For the remaining 60%, we believe manufacturers could produce a panel with a UF resin that complies with the proposed Phase 1 standard. Manufacturers could do some or all of the following:

- Improve manufacturing process controls to increase efficiency, energy use, and reduce waste;
- Use a lower mole ratio UF resin with a F:U mole ratio of approximately 1.3 or less;
- Use scavengers or catalysts; and/or
- Co-blend their base UF resin with a very low mole ratio UF resin (< 1.0).

Through application of all or some of these actions, it is reasoned that the cost of a Phase 1 compliant HWPW panel would be increased by about 1%, due entirely to the increase in resin cost (Appendix G). For example, based on the wholesale price of a HWPW panel presently available for sale of approximately \$20 (Pittsburgh Forest Products, 2007), the projected wholesale price of a Phase 1 panel would be approximately \$20.25. This increase would apply to both veneer core and composite core products.

To meet the proposed Phase 2 standards, it is likely that manufacturers would have optimized their production controls and determined the essential pre-processing treatments needed to reduce manufacturing losses. To reduce HCHO emissions further, manufacturers could choose to use one of three resin systems: MUF, PVA, or soy. In the case of Columbia Forest Products, the decision to develop and use a soy-based resin for their entire HWPW product line was not based solely on cost, and as such, cannot be considered in this context. The Columbia Forest Products Purebond™ is proprietary, however, if the soy resin technology is publicly available in the future, then another low cost option would be available. Rather, the estimate contained herein is based on the use of a MUF resin containing 15% melamine or PVA. For the MUF resin, hexamine addition may be another cost-competitive option (Kamoun et al., 2003). In addition to increased resin costs over UF, it was further assumed that processing times would be lengthened by 10% and 20%, respectively. Through the use of either of these resins, it is reasoned that the cost of Phase 2 compliant HWPW panel would be increased by approximately 8% to 19%. As in the previous example, the projected wholesale price of a Phase 2 panel would be between \$21.50 to \$23.75, for either a veneer core or composite core product.

The above estimated “per panel” increases were used to calculate the total cost to the HWPW industry. Using production data for 2002, where California consumption was estimated to be approximately 299-million ft<sup>2</sup> or 9.3-million panels (Note: a panel is 4' x 8' board or 32ft<sup>2</sup>), and considering that 40% of the HWPW for California already complies with both the Phase 1 and Phase 2 standards, the total cost to the HWPW industry is estimated to be approximately \$6 million per year for Phase 1 and about \$17 million per year for Phase 2.

b. Particleboard (PB)

Based on the CARB 2003 Survey, approximately 55% of PB produced in the U.S. complies with the proposed Phase 1 standard, and only a small amount of

specialty products (< 1%) comply with the proposed Phase 2 standard. For the approximately 45% of U.S. production that does not produce a panel that would comply with the proposed Phase 1 standard, it is projected that to produce a panel with a UF resin that complies with the standard, manufacturers could do some or all of the following:

- Improve manufacturing process controls to increase efficiency, energy use, and reduce waste;
- Use a lower mole ratio UF resin with a F:U mole ratio of approximately 1.1 or less;
- Use scavengers or catalysts; and/or
- Co-blend their base UF resin with a very low mole ratio UF resin (< 1.0).

Through application of all or some of these actions, it is reasoned that the cost of a Phase 1 compliant PB panel would be increased by approximately 4% to 7%, due almost entirely to the increase in resin cost (Appendix G). For example, based on the wholesale price of a PB panel presently available for sale of approximately \$10.50 (Random Lengths, 2007), the projected wholesale price of a Phase 1 panel would be between \$11 and \$11.80.

For the proposed Phase 2 standards, it is likely that manufacturers would have optimized their production controls and determined the essential pre-processing treatments that need to be done to reduce manufacturing losses. To reduce HCHO emissions further, manufacturers could choose to use one of two resin systems: MUF or PF. As manufacturers will likely continue using UF resins, the estimate contained herein is based on the use of a MUF resin containing 8% melamine in combination with the use of lower mole ratio urea-formaldehyde resins (i.e. F:U <1). In addition to increased resin costs over UF, it was further assumed that processing times would be lengthened by approximately 10%. Through the use of MUF resin, it is reasoned that the cost of Phase 2 compliant PB panel would be increased by approximately 17% to 30%. As in the previous example, the projected wholesale price of a Phase 2 panel would be between \$12.30 and \$13.80.

The above estimated “per panel” increases were used to calculate the total cost to the PB industry. Using production data for 2002, where California consumption was estimated to be approximately 600-million ft<sup>2</sup> or 19.5-million panels (Note: a panel is 4' x 8' board or 32 ft<sup>2</sup>), and considering that 55% of current U.S. production already complies with the Phase 1 standard, the total cost to the PB industry is estimated to be approximately \$4-million per year for Phase 1 and approximately \$61-million per year for Phase 2.

c. Medium Density Fiberboard (MDF)

Based on the CARB 2003 Survey, approximately 25% of MDF produced in the U.S. complies with the proposed Phase 1 standard, and only a small amount of

specialty products (< 1%) comply with the proposed Phase 2 standard. For the approximately 75% of U.S. production that does not produce a panel that would comply with the proposed Phase 1 standard, it is projected that to produce a panel with a UF resin that complies with the standard, manufacturers could do some or all of the following:

- Improve manufacturing process controls to increase efficiency, energy use, and reduce waste;
- Use a lower mole ratio UF resin with a F:U mole ratio of approximately 1.1 or less;
- Use scavengers or catalysts; and/or
- Co-blend their base UF resin with a very low mole ratio UF resin (< 1.0).

Through application of all or some of these actions, it is reasoned that the cost of a Phase 1 compliant PB panel would be increased by approximately 4% to 6%, due almost entirely to the increase in resin cost (Appendix G). For example, based on the wholesale price of a PB panel presently available for sale of approximately \$14.00 (Random Lengths, 2007), the projected wholesale price of a Phase 1 panel would be between \$14.50 and \$15.

For the proposed Phase 2 standards, it was postulated that manufacturers would have optimized their production controls and determined the essential pre-processing treatments that needed to be done to reduce manufacturing losses. While pMDI hybrid resins have been found to be effective, the high cost of pMDI precludes its consideration in this analysis. As manufacturers will likely continue using UF resins, the estimate contained herein is based on the use of a MUF resin containing 12% melamine in combination with the use of lower mole ratio urea formaldehyde resin (F:U<1). In addition to increased resin costs over UF, it was further assumed that processing times would be lengthened by approximately 10%. Through the use of this MUF resin, it is reasoned that the production cost of a Phase 2 compliant MDF panel would be increased about 26%. As in the previous example, the projected wholesale price of a Phase 2 panel would be approximately \$17.60. A few manufacturers produce MDF with pMDI, however, pMDI is much more costly than urea- formaldehyde resins (see Table VIII-14). The cost of an MDF panel made from pMDI would be increased by about 135%, due to the increase in resin cost. This increase in resin cost would increase the production cost of a \$14.00 MDF panel to about \$30. So, staff believes that manufacturers would opt for less expensive melamine fortified lower ratio urea formaldehyde resins to meet the Phase 2 emission standard.

The above estimated “per panel” increases were used to calculate the total cost to the PB industry. Using production data for 2002, where California consumption was estimated to be approximately 280-million ft<sup>2</sup> or 8.7-million panels (Note: a panel is 4' x 8' board or 32 ft<sup>2</sup>), and considering that approximately 25% of current U.S. production already complies with the Phase 1 standard, the total cost to the PB industry is estimated to be approximately

\$9-million per year for Phase 1 and approximately \$49-million per year for Phase 2.

d. Total Combined Cost to the Industry

For Phase 1, the total combined cost to HWPW, PB, and MDF manufacturers in the U.S. is estimated to be \$19-million per year, and for Phase 2, \$127-million per year (Appendix G).

**D. Distributor and Importer Costs**

Distributors and importers play an important role in the distribution of composite wood products to the California marketplace. While they do not typically “add value” to panels or finished goods that contain HWPW, PB, and/or MDF, they are the principal entities that resell products to fabricators and retailers. As a significant portion of the HWPW, PB, and MDF that is offered sale or supply in California is handled by distributors or importers, their adherence to the chain-of-custody requirements of the proposed ATCM are fundamental to ensuring the availability and use of CARB-compliant HWPW, PB, MDF, and finished goods containing those materials in California.

**1. Distributors**

Distributors are individuals or business entities to whom HWPW, PB, MDF, or finished goods containing those materials are sold or supplied to, from domestic sources, for the purposes of resale or distribution into commerce. In large part, the major portion of distributors are familiar with the wide range of composite wood products that are presently available for sale or supply in California, and understand that there is a growing demand for “green” products, that are environment-friendly. A growing segment of the green-products industry is building materials made with no added HCHO resins (Tables V-22, V-24, and V-26), which are typically requested by individuals with chemical sensitivities and/or builders pursuing Leadership in Energy and Environmental Design (LEED) credits (U.S. Green Building Council, 2005). The increased availability of low HCHO emission PB, MDF, and HWPW, may require distributors to track some additional stock keeping unit (SKU) numbers for Phase 1 and Phase 2 compliant materials.

Presently, with a growing interest in green building efforts focused on documenting the use of energy-efficient and/or products with specified sustainably harvested wood contents, distributors already participate in one or more chain-of-custody and labeling programs to assure that green-products are supplied to customers that request them. With respect to the use of sustainably harvested wood, the Forest Stewardship Council oversees one of the most widely recognized programs to verify the use of sustainable forest management practices and chain-of-custody programs (Forest Stewardship Council, 1996).

Through programs of this kind, a major portion of distributors are familiar with the level of resources (manpower and cost) that need to be expended to participate in a program of this kind and recognize the beneficial aspects of their participation. It is projected that requiring distributors to track their purchases and sales of CARB-compliant HWPW, PB, and MDF, would not constitute a significant increase in the efforts currently being done to comply with on-going chain-of-custody efforts, such as for the Forest Stewardship Council or the USEPA's National Emission Standards for Hazardous Air Pollutants regulation for composite wood products facilities (USEPA, 2002).

As distributors may secure goods for customers outside of California, they may incur costs for keeping separate records for non-compliant HWPW, PB, and MDF destined for their non-California customers. These costs may be due to maintaining separate data management systems, storage facilities, and labels for California and non-California goods.

## **2. Importers**

Importers are individuals or business entities to whom HWPW, PB, MDF, or finished goods containing those materials are sold or supplied to from overseas sources, for the purposes of resale or distribution into commerce. In large part, importers (e.g., members of the International Wood Products Association) are familiar with the wide range of composite wood products that are presently available for sale or supply in California, and initiate agreements throughout the world for products of lower cost and/or made from rare tree species. As manufacturers, such as Masisa in Chile, supply E1-compliant products to Europe, and Chinese manufacturers supply F☆☆☆ and F☆☆☆☆ products to Japan, importers are well aware of the different emission and strength standards that exist across the world. Imported products are also being supplied to fulfill demand for green-products, as the availability of green-products is limited from U.S. manufacturers. As for distributors of domestic composite wood products, an increase in the availability of low HCHO emission PB, MDF, and HWPW, may require importers to track some additional stock keeping unit (SKU) numbers for Phase 1 and Phase 2 compliant materials.

As for distributors of domestic goods, importers are familiar with the level of resources (manpower and cost) that need to be expended to participate in chain-of-custody and labeling programs and recognize the beneficial aspects of their participation. It is projected that requiring importers to track their purchases and sales of CARB-compliant HWPW, PB, and MDF, would not constitute a significant increase in the efforts currently being done to comply with on-going chain-of-custody efforts, such as for the Forest Stewardship Council (Forest Stewardship Council, 1996).

As importers may secure goods for customers outside of California, they may incur costs for keeping separate records for non-compliant HWPW, PB, and MDF

destined for their non-California customers. These costs may be due to maintaining separate data management systems, storage facilities, and labels for California and non-California goods.

## **E. Fabricator Costs**

Fabricators are individuals or business entities that use HWPW, PB, or MDF to make other goods that are sold or supplied in California. Assuming that a major portion of fabricators purchase HWPW, PB, or MDF on an as-needed basis to fill their orders to customers, they would not maintain large surpluses of panels or components in their places of business. To comply with the proposed ATCM, it is estimated that fabricators may incur additional costs due to higher material costs, and depending on their participation in existing chain-of-custody and labeling programs, may incur additional costs to implement a rigorous record-keeping system to track their purchases and sales of compliant and non-compliant goods.

### **1. Case Studies**

In the following subsections, three case studies were examined as a means to gauge the potential increase in cost to fabricators that elect to build products with HWPW, PB, and/or MDF that complies with the proposed Phase 2 standards (Table VI-1). As environment-friendly products are currently being sold as a separate product line (e.g., Neil Kelly Cabinets, Portland, OR), for sales to medium- or high-price point customers, increases in the cost of HWPW, PB, and/or MDF used to fabricate products in 2009-2012 will likely be passed on to the customer.

#### **a. Furniture**

For furniture to be sold or supplied to California, any furniture maker that elects to build furniture with CARB-compliant HWPW, PB, and/or MDF, would only be in competition with other furniture makers that must incur the same composite wood costs as they do. Presently, aside from upgrading their record-keeping programs to be able to demonstrate the use of CARB-compliant composite wood products, it is not anticipated that the use of these materials would require any specialized equipment or tools for furniture makers than would be required for the use of non-compliant wood products. Should a furniture maker elect to make furniture for customers in California and out-of-state, and deciding to use both CARB- and non-compliant composite wood products, added costs associated with keeping separate records and work/storage areas for those products may be incurred.

In discussions with the American Home Furnishings Alliance, familiarity with the USEPA's chain-of-custody requirements for plywood and composite wood products facilities provides a template for complying with the chain-of-custody requirements for the proposed ATCM.

b. Cabinets

For cabinets to be sold or supplied to California, any cabinet maker that elects to build cabinets with CARB-compliant HWPW, PB, and/or MDF, would only be in competition with other cabinet makers that must incur the same composite wood-related costs as they do. Presently, aside from upgrading their record-keeping programs to be able to demonstrate the use of CARB-compliant composite wood products, it is not anticipated that the use of these materials would require any specialized equipment or tools for cabinet makers than would be required for the use of non-compliant wood products. Should a cabinet maker elect to make cabinets for customers in California and out-of-state, requiring the use both CARB- and non-compliant composite wood products, they may incur added costs for keeping separate records and work/storage areas for those products.

In discussions with the Kitchen Cabinet Manufacturers Association, for large cabinet makers that have captive HWPW, PB, or MDF manufacturing facilities, substantial investments may be needed to upgrade those facilities given that all the composite wood that is produced is used to build cabinets. This industry is not as familiar with chain-of-custody programs as the furniture industry, and as such, is likely to incur some costs in initiating a program and in its day-to-day operation.

c. Windows and Doors

For windows and interior doors to be sold or supplied to California, window/door manufacturers that elects to build windows and interior doors with CARB-compliant HWPW, PB, and/or MDF, would only be in competition with other manufacturers that must incur the same composite wood-related costs as they do. Presently, aside from upgrading their record-keeping programs to be able to demonstrate the use of CARB-compliant composite wood products, it is not anticipated that the use of these materials would require any specialized equipment or tools for window and door manufacturers than would be required for the use of non-compliant wood products. Should a window/door manufacturer elect to make products for customers in California and out-of-state, requiring the use both CARB-compliant and non-compliant composite wood products, they may incur added costs associated with keeping separate records and work/storage areas for those products.

In discussions with the Window and Door Manufacturers and the Door and Access System Manufacturers Associations, concern was expressed relative to potential costs associated with having to recertify the fire- and storm-ratings of their products with organizations such as Underwriters Laboratory. As certifications of this kind cost in excess of \$1,000 a piece, manufacturers were not certain if the use of CARB-compliant HWPW, PB, or MDF would substantially alter their products such as to require recertification testing. In conversations with Underwriters Laboratory, staff learned that nearly all changes of this kind

may be subject to an engineering evaluation, and would not require product recertification.

## **F. Retailer Costs**

Retailers are individuals or business entities that sell, supply or offer for sale HWPW, PB, or MDF, in either finished goods or in panel form to the public-at-large (i.e., consumers). To comply with the proposed ATCM, beginning in 2009, retailers need to clear their inventories of non-compliant products consistent with the sell-through provisions in Table VI-6. A major effort may be needed to inform their suppliers, foreign and domestic, that they must verify that their products are compliant with the proposed ATCM. As such, retailers need to develop a record-keeping system to track where they purchase the merchandise they sell to consumers, and maintain documentation that verifies that the products they sell comply with applicable Phase 1 or Phase 2 standards (i.e. chain-of-custody).

Through contacts made at public workshops, efforts have already been made by a major retailer to secure composite wood products that comply with the European E1 standard. Presently, products meeting the E1 standard are subject to more stringent HCHO emission requirements than are required in the U.S., which may be more costly to sell than products meeting less stringent standards, such as the 1985 HUD standard for products used in mobile homes. With action of this kind already taking place, there may be a greater level of familiarity within the retail sector concerning low HCHO emitting composite wood products, and the efforts needed to assure their quality by the time the ATCM goes into effect.

## **G. Consumer Costs**

In the following subsections, projected increases in the price of HWPW, PB, and MDF panels, and resultant increases in the cost of a small home, large home, and a typical home remodeling project, and a low-price point article of furniture are estimated.

### **1. Incremental Increase in the Cost of a Standard Panel**

Previously, in Tables VIII-12, VIII-14, and VIII-16, estimates of the price increases for PB, MDF, and HWPW manufactured to comply with proposed Phase 2 standards were calculated, respectively. In the following analysis, it is assumed that the approximate increase in the production cost of PB, MDF, and HWPW compliant with the applicable Phase 2 Standard in 2010-2012 would be 30%, 40%, and 15% higher than the wholesale cost of non-compliant products sold in markets outside of California (Table VIII-17). Based on the prices of standard-size panels sold today, in the post Phase 2 timeframe, the production cost of a standard PB, MDF, and HWPW panel is estimated to be approximately \$3 to \$4, \$4 to \$6, and \$5 to \$7 higher than a comparable panel made with UF resin, depending on the thickness of the panel.

Table VIII-17. Estimated Cost of Particleboard, Medium Density Fiberboard, and Hardwood Plywood Panels Following the Effective Date of the Phase 2 Standard <sup>1</sup>

	----- Board Thickness -----			
Particleboard	3/8"	1/2"	5/8"	3/4"
Pre-Phase 2 Effective Date	\$9.15	\$9.57	\$10.66	\$11.90
Post Phase 2 Effective Date	\$11.90	\$12.44	\$13.86	\$15.47
Estimated Increase	\$2.75	\$2.87	\$3.20	\$3.57
Medium Density Fiberboard	3/8"	1/2"	5/8"	3/4"
Pre-Phase 2 Effective Date	\$9.89	\$11.01	\$12.86	\$14.53
Post Phase 2 Effective Date	\$13.85	\$15.41	\$18.00	\$20.34
Estimated Increase	\$3.96	\$4.40	\$5.14	\$5.81
Hardwood Plywood	1/2" Birch	3/4" Birch	3/4" Oak	3/4" Maple
Pre-Phase 2 Effective Date	\$33.95	\$39.99	\$42.99	\$38.00
Post Phase 2 Effective Date	\$39.04	\$45.99	\$49.43	\$43.70
Estimated Increase	\$5.09	\$6.00	\$6.44	\$5.70

(<sup>1</sup>) Random Lengths (2006b). Pre-Phase 2 and Post Phase 2 dollar values are for a standard 4' x 8' panel.

## 2. Increase in Material Cost for New Home Construction

In this analysis of incremental new house construction, staff found that the increase in construction cost would be less than 0.1%. These costs are relative to statistics from the National Association of Realtors, which show the 2006 average median home price for four southern California cities to be \$574,000 (National Association of Realtors, 2007).

### a. Two-bedroom House

Staff estimated the incremental cost of a one story, one bath, 800 ft<sup>2</sup> house (Appendix F). To develop the estimate, a building plan house was obtained (Dream House Source, Not Dated (a)), and commercially available software was used to calculate the amount of composite wood materials that would be used to build the kitchen and bathroom cabinets, where the major portion of the HWPW, PB, and MDF is used in a home (Planit Solutions, Inc., 2004). Based on the total amount of HWPW, PB and MDF estimated, the incremental "per panel" production cost was then applied. Based on this incremental cost analysis, staff found that the increased cost of construction for an 800 ft<sup>2</sup> house is about \$200. Assuming that the incremental increase in construction cost is added to the price

of a median priced home of \$574,000, the estimated increased cost is about 0.03%.

Alternatively, housing costs can be calculated a different way. If the proposed ATCM industry-wide cost increase for Phase 2 (\$127 million) is assumed to be applied to new housing starts, then an overall cost per new house can be determined. According to real estate statistics, the two year average (2004 to 2005) for California housing starts (single family homes and multi-family units) was about 200,000 per year (California Building Industry Association, 2006; Not Dated). If it is assumed that 50% of the HWPW, PB, and MDF for California is used for new home construction, then the overall increase would be \$300 per new home (i.e.,  $(\$127 \text{ million} \times 0.5) \div 200,000 = \$300$  per housing start).

b. Four-bedroom House

To develop this estimate, staff performed the same analysis as the two-bedroom house, but based on the building plan for a four bedroom, three bath home (Dream House Source, Not Dated (b)). As Appendix F describes, the incremental construction cost of a 2,000 ft<sup>2</sup> house is about \$390. Therefore, assuming this increase in construction cost is added to the price of a median priced home of \$574,000, the estimated increased cost is about 0.07%.

In the context of existing profit margins for large home builders, which range from 8 to 16%, the increase in material cost of composite wood products poses an insignificant factor in the cost of new home construction.

c. Remodeling Project

The average cost of a kitchen remodel ranges from \$15,000 to \$25,000, where the cost of the cabinets is a major portion of the cost. Depending on the size of the home being remodeled, the cost of the composite wood materials used to build the cabinets and countertops may range from \$400 to \$600 at present-day prices (Tables VIII-18 and VIII-19), while the purchase price of the cabinets would be ten- to 15-times higher. Assuming the mix of wood products identified previously would still be used, the increase in material cost is estimated to range from 26 to 27%. At this level of increase, the cost of composite wood materials used to build the cabinets in a kitchen remodeling project would rise by \$104 to \$160. This represents a 1% increase to the cost of a remodeling project.

**3. Increase in Material Costs for Low Price Point Case Goods**

Particleboard is used to manufacture a wide variety of low price point case goods, such as pre-assembled or ready-to-assemble book cases. Assuming that the cost of Phase 2-compliant PB will be more expensive than currently available panels, an estimate of how much the cost of the PB in a pre-assembled book case would increase, in consideration of the previously developed cost

estimate for 2-compliant PB (Table 14). For purposes of this analysis, it was assumed that bookcases built with MDF or HWPW would be medium price point commodities and less affected by the projected increases in PB cost that could have a significant impact on the viability of low price point case goods.

For a typical four-shelf bookcase (79" height x 29" width x 11" depth), the following amounts of PB are used:

- one 4' x 8' panel of ¾" PB for the shelves and side panels;
- one 4' x 8' panel of ⅜" PB for the back; and
- one 2' x 8' panel of ¾" PB for the top and bottom rails, frames, etc.

Assuming a present-day cost of a ¾" panel at \$11.90 and a ⅜" panel at \$9.15 (Table 14), the total cost of PB used to build the above bookcase would be \$27.00 (i.e.,  $[(1\frac{1}{2} \times \$11.90) + \$9.15] = \$27.00$ ). To bracket the range of prospective cost increases, it is assumed that the cost of resin used to make Phase 2-compliant PB could range from 15 to 100% more expensive than UF resin. At 15%, the estimated increase in PB cost would be \$1.22, bringing the total cost of PB to \$28.22, a 5% increase over the present-day cost. At 100%, the estimated increase in PB cost would be \$8.10, bringing the total cost of PB to \$35.10, a 30% increase over the present-day cost.

## **H. Impacts to Small Business**

As all HWPW, PB, MDF, and finished goods offered for sale or supply in California will be required to meet the proposed Phase 1 and Phase 2 standards in 2009 to 2012, there should be no specific detrimental impact on small business, and all entities in the distribution chain would be required to use or sell compliant products.

## **I. References**

Akzo Nobel. 2005. Kenocatch 4315L. Product information, Casco Adhesives, Sundsvall, Sweden. 2 pp.

American Plywood Association (APA). 2003. The Engineered Wood Association Market Outlook. Structural Panels and Engineered Wood 2003-2008. From: [http://www.cintrafor.org/CONFERENCE\\_TAB/ifpm%202003/Presentations/AdairCintra%2003.pdf](http://www.cintrafor.org/CONFERENCE_TAB/ifpm%202003/Presentations/AdairCintra%2003.pdf) Accessed: 28 January, 2007.

Answers.com. Not Dated. Hardwood Veneer and Plywood: Information From Answers.com. From: <http://answers.com/topic/hardwood-veneer-and-plywood> Accessed: 25 January 2006.

Bomersheim W. Not Dated. A quick look at the best growth hardwood import markets based on current trends.

CARB. 2003. Analysis of Data Collected in the CARB 2003 Composite Wood Products Survey of Products Offered for Sale in 2002. Unpublished data.

Cognard P. 2005. Woodworking and furniture adhesives. Part 5: Applications and end uses. Accessed: 20 September 2006. From: <http://www.specialchem4adhesives.com/resources/articles/printarticle.aspx?id=1235>

Columbia Forest Products. 2006. Purebond™. Product Information, Columbia Forest Products, Portland, OR. 2 pp.

Composite Panel Association (CPA). 2006. 2005 North American Shipments Report: Particleboard, Medium Density Fiberboard, Hardboard. CPA, Gaithersburg, MD. 18 pp.

CPA. 2007. Welcome to the Composite Panel Association. From: <http://www.pbmdf.com/AboutCPA/index.asp> Accessed: 5 January 2007.

CPA. ND. Buyers and Specifiers Guide to North American Particleboard, Medium Density Fiberboard, and Hardboard Products and Manufacturers: 2006. From: <http://www.pbmdf.com/aboutCPA/memberdirectory.asp> Accessed: 10 July 2006.

Dream House Source. Not Dated (a). Home Plan 9802. Accessed: 20 July 2006. From: <http://www.dreamhousesource.com/Plan.asp?PlanID=9802>

Dream House Source. Not Dated (b). Home Plan 18401. Accessed: 20 July 2006. From: <http://www.dreamhousesource.com/Plan.asp?PlanID=18401>

Encyclopedia of American Industries. 2007. SIC 2435: Hardwood veneer and plywood. Available: [www.referenceforbusiness.com/industries/Lumber-Wood/Hardwood-Veneer-Plywood.html](http://www.referenceforbusiness.com/industries/Lumber-Wood/Hardwood-Veneer-Plywood.html) Accessed: 30 January, 2007

Forest Stewardship Council. 1996. Chain-of-custody. Fact sheet, 2 pp.

Frihart CR. 2005. Chapter 9: Wood adhesion and adhesives, p. 215-278. In: RM Rowell (ed). Handbook of Wood Chemistry and Wood Composites. CRC Press, Boca Raton.

Global Trade Atlas. Wood Products Imports. Not Dated. From: [http://www.fas.usda.gov/ffpd/wood\\_products\\_presentations/world\\_importers/world's\\_leading\\_wood\\_product\\_importers.pdf](http://www.fas.usda.gov/ffpd/wood_products_presentations/world_importers/world's_leading_wood_product_importers.pdf) Accessed: 28 January 2007.

- Global Wood Trade Network. 2005. Veneer, plywood and engineered wood product manufacturing in the U.S. Accessed: 28 January 2007. From: <http://www.globalwood.org/market1/news20050501.htm>
- Global Wood Trade Network. 2007. China wood products prices. Accessed: 28 January 2007. From: <http://www.globalwood.org/market1/aaw20070101d.htm>
- Goldboard Development Corporation. 2000. Overview of Goldboard® Products. From: <http://www.goldboard.com/products/products.html> Accessed: 12 December 2001.
- Hardwood Plywood and Veneer Association (HPVA). 2007. List of Email from Bill Altman to Angela Csondes.
- Home Depot. 2006. Product information table: Plywood. Accessed: 20 September 2006. From: <http://homedepot.bighammersoftware.com>
- Howard, JL. 2001. United States Department of Agriculture (USDA). U.S. Timber Production, Trade, Consumption, and Price Statistics 1965-1999.
- Howard JL. 2005. U.S. Forest Products Annual Market Review and Prospects, 2001-2005. Research Note FPL-RN-0299, USDA, Forest Service, Forest Products Laboratory, Madison, WI. 11 pp.
- Industry Canada. 2005a. Wood-based panel products: Technology roadmap. I. Introduction and overview. From: <http://strategis.ic.gc.ca/epic/internet/infif.nsf/en/oc01504e.html> Accessed: 13 April 2006.
- Industry Canada. 2005b. Wood-based panel products: Technology roadmap. II. Panels in perspective. From: <http://strategis.ic.gc.ca/epic/internet/infif.nsf/en/oc01505e.html> Accessed: 13 April 2006.
- Kamoun C, A Pizzi, and M Zanetti. 2003. Upgrading melamine-urea-formaldehyde polycondensation resins with buffering additives. I. The effect of hexamine sulfate and its limits. *Journal of Applied Polymer Science*, 90: 203-214.
- Marutzky R. 1989. Chapter 10: Release of formaldehyde by wood products. In: Pizzi A (ed). 1989. *Wood Adhesives: Chemistry and Technology*, Volume 2: 307-388.
- National Association of Home Builders (NAHB). Not Dated. *Housing: 2004 Facts, Figures & Trends*. NAHB, Public Affairs, Washington, DC. 50 pp.
- NAHB. 2006. Median and average price per square foot of floor area in new one-family houses sold by location. Accessed: 7 February 2007. From: [http://www.nahb.org/fileupload\\_details.aspx?contentID=560](http://www.nahb.org/fileupload_details.aspx?contentID=560)

Oakwood Veneer Company. 2006a. Company Price List: 4' x 8' A-B. From: [http://www.oakwoodveneer.com/prices/prices4\\_8\\_ab.html](http://www.oakwoodveneer.com/prices/prices4_8_ab.html) Downloaded: 19 September 2006.

Oakwood Veneer Company. 2006b. Company Shopping Cart: 3-ply Veneer. From: [https://oakwoodveneer.com/shop/shop\\_3ply.html](https://oakwoodveneer.com/shop/shop_3ply.html) Downloaded: 20 September 2006.

Osman Z, A Pizzi, W Kantner, and MC Triboulot. 2005. PUF panel adhesives doped with additional urea and reinforced by isocyanates. *Holz als Roh- und Werkstoff*, 63: 53-56.

Pittsburgh Forest Products Company. 2007. Unit cost price for hardwood plywood panels. From: <http://www.sticktrade.com/members/5425.htm> Accessed: 26 February 2007.

Pizzi A. 1994. *Advanced Wood Adhesives Technology*. Marcel Dekker, Inc., New York. 289 pp.

Planit Solutions, Inc. 2004. cabinetware case planner. Product brochure. From: <http://www.planitsolutions.com/us/cabinetware/global.forms.brochure.aspx?brand=3> Accessed: 29 August 2006.

Random Lengths. 2006a. *Forest Product Market Prices and Statistics: 2005 Yearbook, Volume LXI*. Random Lengths Publications, Inc., Eugene, Oregon. 312 pp. [ISBN: 1-884311-23-7]

Random Lengths. 2006b. Panel price guide: Monthly average for June 2006. *Yardstick*, 16(6): 18.

Random Lengths. 2007. Panel price guide: Monthly average for January 2007. *Yardstick*, 17(1): 18.

Schuler A. 2006. Construction markets & building material prices: How strong is the relationship? *Structural Building Components Magazine*, March 2006: 20-23.

Sellers T Jr. 2001. Wood adhesive innovations and applications in North America. *Forest Products Journal*, 51(6): 12-22.

Spelter H. 1989. Plywood Manufacturing Cost Trends, Excluding Wood, in Western U.S. Mills: 1975-1988. General Technical Report FPL-GTR-64. USDA, Forest Service, Forest Products Laboratory, Madison, WI. 12 pp.

Spelter H. 1992. HCHO emissions debate invites scrutiny of lab tests, economics. *Panel World*, March 1992: 22-24.

U.S. Census Bureau. 2003. 2002 NAICS Definitions: 321 Wood Product Manufacturing. Accessed: 5 January 2007. From: <http://www.census.gov/epcd/naics02/def/NDEF321.HTM#N3212>

U.S. Census Bureau. 2006a. California: 2004 County Business Patterns. U.S. Department of Commerce, CBP/04-6.

U.S. Census Bureau. 2006b. United States: 2004 County Business Patterns. U.S. Department of Commerce, CBP/04-1.

U.S. Census Bureau. Not Dated. Timber Products. Production, Foreign Trade and Consumption by Type of Product. Accessed: 7 February 2007. From: <http://www.census.gov/compendia/statab/tables/07s0858.xls>

U.S. Department of Agriculture. Not Dated (a). Foreign Agricultural Service (FAS) Import Commodity Aggregations: People's Republic of China. From: <http://www.fas.usda.gov/ustrdscripsts/usreport.exe> Accessed: 26 January 2007.

U.S. Department of Agriculture. Not Dated (b). Import situation & outlook for wood. From: [http://www.fas.usda.gov/ffpd/wood\\_publicatons.htm](http://www.fas.usda.gov/ffpd/wood_publicatons.htm) Accessed: 26 January 2007.

USEPA. 2002. Economic Impact Analysis of the Proposed Plywood and Composite Wood Products NESHAP. Final Report, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.

USEPA. 2004. Regulatory Impact Analysis for the Plywood and Composite Wood Products NESHAP. Final Report, EPA-452/R-04-005, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

U.S. Green Building Council. 2005. Leadership in Energy and Environmental Design. From: <http://www.usgbc.org/DisplayPage.aspx?CategoryID=19> Accessed: 9 November 2005.

Westcott JM and CR Frihart. 2004. Competitive soybean flour/phenol-formaldehyde adhesives for oriented strandboard. In: Tichy RJ and V Yadama (eds). 38<sup>th</sup> International Wood Composites Symposium Proceedings, p. 199-206. Washington State University, Pullman, WA.

Wood Based Panels International. 2006. Vol. 26. No. 5. October/November

Youngquist JA. 1999. Chapter 10: Wood-based composites and panel products. In: Forest Products Laboratory. Wood Handbook – Wood as an Engineering Material. General Technical Report FPL-GTR-113. USDA, Forest Service, Forest Products Laboratory, Madison, WI. 31 pp.

## **IX. Environmental Impacts of the Proposed Airborne Toxic Control Measure**

The primary intent of the proposed ATCM is to protect public health by reducing emissions of and human exposure to HCHO released from composite wood products. The proposed ATCM also provides air quality benefits by reducing ozone formation, as HCHO is a compound that undergoes atmospheric transformations to form ozone. In consideration of the data analyses performed herein, staff has determined that no significant adverse environmental impacts should occur as a result of adopting this ATCM. This chapter describes the potential impacts that the proposed ATCM may have on the environment.

### **A. Legal Requirements**

The California Environmental Quality Act (CEQA) and CARB policy require an analysis be performed to determine the potential adverse environmental impacts of proposed regulations. To meet this requirement, CARB must assess the extent and severity of reasonably foreseeable environmental impacts, and respond (in writing) to all significant environmental issues raised in the public review period and at the Board hearing. Presently, CARB's regulatory program is certified by the Secretary of Resources (cf. Public Resources Code §21080.5), which allows CARB to include an environmental analysis in the Initial Statement of Reasons (ISOR) instead of preparing an environmental impact report or negative declaration. Written responses to significant environmental issues raised by the public will be included in the Final Statement of Reasons (FSOR) for the ATCM.

Public Resources Code §21159 requires that the environmental analysis prepared by CARB include analyses of the following "reasonably foreseeable" items:

- Impacts of the methods of compliance;
- Feasible mitigation measures; and
- Alternate means of compliance with the ATCM, (see subsection VII.G.).

With respect to mitigation measures, CEQA requires state agencies to identify and adopt feasible mitigation measures that would minimize any significant adverse environmental impacts described in the environmental analysis.

### **B. Analysis of Reasonably Foreseeable Environmental Impacts**

To manufacture HWPW, PB, and MDF that complies with the proposed Phase 1 and Phase 2 standards, manufacturers may choose to use an alternative resin instead of UF, or modify their existing UF resin through the use of additives. A discussion of the potential health effects from the use of isocyanates, melamine,

phenol and soy flour is provided below and in subsection VII.G. of this staff report. The principal compounds considered in the following evaluation are:

- Phenol (from PF resins);
- Melamine (as an additive to UF resins);
- Polyvinyl acetate (as a no added HCHO adhesive for HWPW);
- Methanol (as an additive/reagent used with UF resins);
- Methylene Diisocyanate (as a no added HCHO adhesive for MDF); and
- Soy flour (as a no added HCHO adhesive for HWPW).

## **1. Air Quality**

In setting new HCHO emission standards for PB, HWPW, and MDF, reductions in statewide HCHO emissions would be expected to occur at all points along the distribution chain. Because HCHO is a VOC, the proposed ATCM would also be reducing an ozone precursor. For example, the use of soy flour-based resins would essentially reduce volatile organic compound emissions to near-zero. As some resin systems have lower energy requirements in their manufacturing process, reductions in carbon dioxide emissions that contribute to global warming would be expected.

Of the projected alternative resin systems, reports indicate that exposure from air may occur for phenol, methanol, and methyl diisocyanate (MDI); however, none of these compounds have been classified as carcinogens by IARC (CARB, 1997a, 1997b; Department of the Environment and Water Resources of the Australian Government, Not Dated; National Oceanic and Atmospheric Administration, 2003). Current typical UF resins can contain methanol, as a co-reactant, however, we believe that Phase 2 emission standards will not result in increase in any methanol use. In fact, we anticipate that the future use of alternative resin systems, may decrease methanol use. Polyvinyl acetate (PVA) contains no hazardous materials under the current OSHA standard and is not listed as a carcinogen by IARC (Franklin International, 2006; Gamblin, 1997). In the workplace, potential respiratory effects from phenol and MDI have been the subject of controls for many years (Gilbert, 1987).

With regard to greenhouse gas emissions, use of an alternative resin system may provide a minor increase or decrease in energy-related carbon dioxide emissions. Overall, it is assumed that California's demand for HWPW, PB, and MDF will continue to be met by manufacturers in the West, resulting in no net change in transport-related carbon dioxide emissions. Although, if the current trend continues, increasing amounts of products could be supplied from overseas manufacturers, whose market share has grown dramatically in the last ten years (Figures VIII-1 to VIII-3). The increase in overseas imports, and associated transport-related carbon dioxide emissions, may in part be due to the U.S. becoming a growing market for high-emitting products from overseas. As such, the establishment of more stringent HCHO emission standards in California may

help to forestall the rising trend in transport-related carbon dioxide emissions, as those products would need to be sold elsewhere and may be sold closer to where they are manufactured.

## **2. Potential Water Quality Impacts**

Use of any of the alternative resins is not expected to pose a significant threat to water quality. Phenol is reported to have a half-life of 2 to 20 days, and does not bioaccumulate in aquatic wildlife (Commonwealth of Australia, 2005). Melamine has a low toxicity to aquatic life, and is effectively degraded by waste-water treatment plants (DSM Melamine, 2002; Organization for Economic Cooperation and Development, Not Dated). Due to its miscibility in water, methanol principally dissolves and dilutes to very low concentrations in the event of surface water exposures (Malcolm Pirnie, 1999). The potential for environmental spills of MDI is low, and releases to water result in the formation of polyurea compounds, with no toxicological effects (Gilbert, 1987; Yakabe et al., 1999).

## **3. Potential Hazardous Waste Impacts**

Potential hazardous waste impacts on soil quality from a spill of the alternative resin systems are not expected to be significant. Phenol can be transported to soil from air or water, and could possibly accumulate in landfills at low levels. Recently, Gusse et al. (2006) demonstrated that biodegradation of phenolic resins could be achieved using white rot fungi, which may provide opportunities for phenolic resin recycling and/or recovery of production constituents. Melamine, if released to soil could pose an accumulation problem, but due to its low toxicity, does not pose a significant environmental risk (Organization for Economic Cooperation and Development, Not Dated). Low concentrations of methanol are unlikely to persist, as it will undergo rapid biodegradation under a wide range of geochemical conditions (Malcolm Pirnie, 1999). Spills of MDI will result in the formation of solid polyurea compounds, whose ecological impacts are likely to be slight and reversible (Gilbert, 1987).

## **4. Potential Bioaccumulation Impacts**

The toxicities of soy flour, PVA, and melamine are low, and as such, bioaccumulation does not pose a significant environmental risk to humans or wildlife. Phenol has a relatively short half-life and does not tend to bioaccumulate (Commonwealth of Australia, 2005). Bioaccumulation of MDI is unlikely due to its high reactivity with hydroxyl radicals in air, and low solubility in water (Gilbert, 1987; Yakabe et al., 1999).

### **C. Reasonably Foreseeable Feasible Mitigation Measures**

Staff has concluded that no significant adverse environmental impacts would occur from implementing the proposed ATCM. As no adverse impacts are anticipated, no mitigation measures would be needed.

### **D. Reasonably Foreseeable Alternative Means of Compliance**

The use of various types of alternative resin systems constitutes the alternative means of compliance with the proposed ATCM. The potential health effects resulting from the use of the alternative resin systems are discussed in Chapter VII of the ISOR. For example, while the use of MDI resin is not expected to be widespread, worker safety protocols have been developed in the U.S. for facilities that may choose to utilize those resins. Based on the data analyses performed and input from public meetings, the proposed HCHO emission limits for PB, HWPW, and MDF are needed to reduce emissions to ambient air and human exposures in homes, schools, and workplaces. The existence of a commercially viable “no added HCHO” technology provides justification for an incremental reduction by all manufacturers in the near-term and more stringent limits in 2011 to 2012.

### **E. Community Health and Environmental Justice**

Environmental justice is a core consideration in CARB’s efforts to provide clean air for all California communities (CARB, 2001). The proposed ATCM, calling for more stringent HCHO emission limits in selected composite wood products, would not cause significant adverse impacts in any community. Rather, implementation of the proposed ATCM is aligned with the principle of pollution prevention, and would likely reduce exposures to HCHO in all communities, including low-income areas and ethnically diverse communities.

### **F. References**

CARB. 1997a. Methanol. In: CARB. Toxic Air Contaminant List Summaries, p. 631-634. Stationary Source Division, Sacramento, CA.

CARB. 1997b. Phenol. In: CARB. Toxic Air Contaminant List Summaries, p. 767-770. Stationary Source Division, Sacramento, CA.

CARB. 2001. Policies and Actions for Environmental Justice. Planning & Technical Support Division, Sacramento, CA. 13 pp.

Commonwealth of Australia. 2005. Phenol. Substance fact sheet. From: <http://www.npi.gov.au/database/substance-info/profiles/70.html> Accessed: 26 February 2007.

Department of the Environment and Water Resources of the Australian Government. 2001. Not Dated. State of Knowledge Report: Air Toxics and Indoor Air Quality in Australia. Methylenebis(phenylisocyanate) MDI. From: <http://www.environment.gov.au/atmosphere/airquality/publications/sok/profiles/methylenebis.html>. Accessed: 26 February, 2007.

DSM Melamine. 2002. Safety Data Sheet: Melamine. Accessed: 26 February, 2007. From: [http://www.dsm.com/en\\_US/downloads/dmm/msdsenglish3.pdf](http://www.dsm.com/en_US/downloads/dmm/msdsenglish3.pdf)

Franklin International. 2006. Material Safety Data Sheet: Titebond II Premium Wood Glue. From: <http://titebond.com/MsdsTB.asp?Frames='Y'&prod=5008> Accessed: 26 February 2007.

Gamblin R. 1997. Material Safety Data Sheet: Poly Vinyl Acetate Glue. From: <http://www.gamblincolors.com/msds/pva.html> Accessed: 26 February 2007.

Gilbert DS. 1987. Fate of TDI and MDI in air, soil, and water. Polyurethanes World Congress 1987: 50 Years of Polyurethanes. From: <http://md1.csa.com>. Accessed: 26 February, 2007.

Gusse AC, PB Miller, and TJ Volk. 2006. White-rot fungi demonstrate first biodegradation of phenolic resin. Environmental Science & Technology, 40: 4196-4199.

Malcolm Pirnie Incorporated. 1999. Evaluation of the Fate and Transport of Methanol in the Environment. Accessed: 26 February, 2007. From: [http://www.erd.llnl.gov/FuelsoftheFuture/pdf\\_files/evaluation.pdf](http://www.erd.llnl.gov/FuelsoftheFuture/pdf_files/evaluation.pdf).

National Oceanic and Atmospheric Administration. 2003. Material Safety Data Sheet: Phenol Liquid. From: <http://www.sefsc.noaa.gov/HTMLdocs/phenol.htm> Accessed: 26 February 2007.

Organization for Economic Cooperation and Development (OECD). Not Dated. SIDS Initial Screening Profile: Melamine. Accessed: 26 February, 2007. From: <http://www.inchem.org/documents/sids/sids/108781.pdf>.

Yakabe Y, KM Henderson, WC Thompson, D Pemberton, B Tury, and RE Bailey. 1999. Fate of methylenediphenyl Diisocyanate and toluene Diisocyanate in the aquatic environment. Environmental Science & Technology, 33: 2579-2583.

