



Research and Development

SOURCES AND FACTORS AFFECTING
INDOOR EMISSIONS FROM
ENGINEERED WOOD PRODUCTS:
Summary and Evaluation of Current Literature

Prepared for

National Risk Management Research Laboratory

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

E. Timothy Oppelt, Director
National Risk Management Research Laboratory

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ABSTRACT

Reconstituted engineered wood components (e.g., particleboard and medium-density fiberboard) are common to several types of consumer wood products (e.g., residential and ready-to-assemble furniture and kitchen cabinets). The selection of resins used to bind the components, coatings, and laminates applied to the components to produce the final products affects emissions of formaldehyde and other volatile organic compounds from the products to the indoor environment. Research Triangle Institute is collaborating with the Indoor Environment Management Branch of the U.S. Environmental Protection Agency's Air Pollution Prevention and Control Division on a cooperative agreement entitled, "The Application of Pollution Prevention Techniques to Reduce Indoor Air Emissions from Composite Wood Products." The research objectives are to characterize indoor air emissions from engineered wood products and to identify and evaluate pollution prevention approaches for reducing indoor air emissions from these products.

The research has a five-phase approach: (1) evaluate existing data and testing methodologies; (2) convene research planning meetings; (3) select high-priority emissions sources; (4) evaluate high-priority emissions sources; and (5) develop and demonstrate pollution prevention approaches for reducing indoor air emissions from high-priority sources. This report summarizes information from the first two phases of research. Information presented here will be used to select reconstituted wood components with various finishing and resin systems for initial emissions screening.

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LIST OF ACRONYMS

ACH	Air changes per hour
APA	American Plywood Association
APPCD	Air Pollution Prevention and Control Division
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing & Materials
CARB	California Air Resources Board
DNPH	Dinitrophenylhydrazine
EPA	Environmental Protection Agency
EPCRA	Emergency Planning and Community Right-to-know Act
ER	Emissions rate
ERG	Environmental Resource Guide
FEV	Forced expiratory volume
FID	Absorbent flame ionization detector
FVC	Forced vital capacity
GC/MS	Gas chromatography-mass spectrometry
GTRI	Georgia Tech Research Institute
HEM	Human exposure model
HPLC	High-performance liquid chromatography
HPVA	Hardwood Plywood and Veneer Association
HUD	Department of Housing and Urban Development
HVAC	Heating, ventilation, and air conditioning
IAB	Indoor Air Branch
IAQ	Indoor air quality
IVOC	Individual volatile organic compound
LEM	Low-emitting materials
MDF	Medium density fiberboard
MDI	Methylenediphenyl diisocyanate
MEK	Methyl ethyl ketone
MIK	Methyl isobutyl ketone
MMSF	Million square feet
NAAQS	National Ambient Air Quality Standards
NCASI	National Council of the Paper Industry for Air and Stream Improvements, Inc.
NEM	NAAQS Exposure Model
NIOSH	National Institute of Occupational Safety and Health
NOAEL	No observed adverse effects level
NPA	National Particleboard Association
NRC	National Research Council
OSB	Oriented strandboard
PB	Particleboard
PF	Phenol formaldehyde
PMDI	Polypolymer methylenediphenyl diisocyanate
PPM	Parts per million
PRF	Phenol resorcinol formaldehyde
PTFE	Polytetrafluorethylene
QA	Quality assurance
RTA	Ready to assemble
RTI	Research Triangle Institute
SARA	Superfund Amendments and Reauthorization Act
SBS	Sick Building Syndrome
SYP	Southern yellow pine
TGNMO	Total gaseous nonmethane organics
TRI	Toxics Release Inventory
TVOC	Total volatile organic compound
UF	Urea-formaldehyde
VOC	Volatile organic compound
WB	Waferboard

CONVERSION TABLE

<u>To Convert from:</u>	<u>To:</u>	<u>Multiply by:</u>
Length		
foot (ft)	meter (m)	0.3048
	centimeter (cm)	30.48
inch (in)	millimeter (mm)	25.4
	cm	2.54
	m	2.54×10^{-2}
Area		
square foot (ft ²)	square centimeter (cm ²)	929
	square meter (m ²)	0.0929
square inch (in ²)	square millimeter (mm ²)	0.06452
	cm ²	6.452
	m ²	6.452×10^{-4}
Area/Volume		
square foot/cubic foot (ft ² /ft ³)	m ² /m ³	3.28
Volume		
ft ³	m ³	0.02817
cubic inch (in ³)	cubic centimeter (cm ³)	16.387
	m ³	1.6387×10^{-5}
Time		
minute (min)	second (s)	60
hour (h)	s	3600
	min	60
Mass		
U.S. ton (t)	Mg	0.9018
	kg	907.18
pound-mass (lb _m)	kg	0.4536
	g	453.6
Temperature		
°F	°C	$5/9(^{\circ}\text{F} - 32)$
Density		
lb _m /ft ³	kg/m ³	16.02
	g/m ³	16,020
	g/cm ³	0.01602
Flowrate/Area		
lb _m /(h · ft ²)	kg/(s · m ²)	0.00136
Velocity (linear)		
ft/min	m/s	5.08×10^{-3}
	cm/s	0.5080
ft/s	m/s	0.3048
	cm/s	30.48

1.0 INTRODUCTION

Existing approaches for improving indoor air quality (IAQ) have frequently focused on control strategies, such as increased or improved ventilation. Although these approaches can result in improved IAQ, they may also be inefficient. It is widely accepted in the IAQ research community that source management is the method of choice to reduce indoor air pollution. Source management in the context of IAQ refers to practices that: (1) reduce the overall source strength; (2) render the source more amenable to control; or (3) eliminate the source entirely. The U.S. Environmental Protection Agency's (EPA's) Air Pollution Prevention and Control Division (APPCD) is responsible for much of EPA's indoor air engineering research and seeks to integrate IAQ and pollution prevention (source reduction) into a strategic approach to indoor source management. APPCD's Indoor Environment Management Branch (IEMB) Pollution Prevention/IAQ research objective is to employ accepted pollution prevention techniques (e.g., process modification and product reformulation) to reduce indoor air contamination through the development of "low-emitting materials" (LEM). An LEM is a material designed to emit fewer emissions when used in the same manner as another material in the same indoor environment.

APPCD is investigating the application of pollution prevention approaches to reduce indoor air emissions from specific indoor sources. The APPCD has selected engineered wood products for the initial phase of their efforts. Engineered wood products can be a significant source of indoor air contamination. Engineered wood products comprise basic building materials, such as underlay, flooring, cabinets, and common furnishings, and are ubiquitous to most indoor settings.

The Research Triangle Institute (RTI) is collaborating with IEMB on a cooperative agreement entitled, "The Application of Pollution Prevention Techniques to Reduce Indoor Air Emissions from Composite Wood Products." The objectives of this research are to characterize indoor air emissions from engineered wood products, then to identify and evaluate pollution prevention approaches such as the development of LEM for use indoors. This research will be conducted in five phases: (1) evaluate existing data and testing methodologies; (2) convene research planning meetings; (3) select high-priority emissions sources; (4) evaluate high-priority emissions sources; and (5) develop and demonstrate pollution prevention approaches for reducing the indoor air emissions from the selected high-priority sources.

This report summarizes information collected in the first two phases of this project. The information presented here, along with information from outside technical advisors, will be used to select products for further research. The technical advisors include trade association representatives, industry representatives, and technical assistance providers. Extensive source characterization will be carried out on the selected products. Pollution prevention approaches will be identified and applied. These improved products will be evaluated through quantitative emissions measurements to determine the technical and economic feasibility, overall pollution prevention potential, and indoor air quality benefits of the pollution prevention approaches.

2.0 SOURCES OF INDOOR EMISSIONS FROM ENGINEERED WOOD PRODUCTS

Research over the past two decades has indicated that engineered wood products can be sources of a large number of organic compounds, particularly formaldehyde. Indoor emissions from engineered wood products can arise from the raw engineered wood (both the wood and resin), the finishing materials applied to the boards for decorative purposes, and the glues used to adhere pieces of engineered wood together. In addition to acting as sources of organic compounds, engineered wood products may also behave as adsorbers and re-emitters of these compounds that are emitted from other sources, such as carpeting, paints, and environmental tobacco smoke (Neretnieks et al., 1993).

Emissions data are abundant in the literature on formaldehyde emissions associated with resins used to bond engineered wood, primarily urea-formaldehyde (UF) resins. Some emissions data also exist on formaldehyde and other organics emitted naturally from the wood. Currently, two major research studies are being conducted to characterize volatile organic compounds (VOC) from various types of raw engineered wood. One of these research studies is being conducted at the U.S. Department of Agriculture's Forest Products Laboratory in Madison, Wisconsin. This research is characterizing emissions from different wood species and UF resins used to construct particleboard (PB). The other research study is being conducted by Forintek, a renowned Canadian forest products laboratory. Forintek is characterizing emissions from different species of wood used to construct oriented strandboard (OSB), another type of engineered wood.

At present there is very little data on how finishing materials contribute to emissions from engineered wood products. Finishing materials in this context mean any type of material added to raw engineered wood such as paper, wood veneer, ink prints, and vinyl. Some of these finishes may contribute to a product's overall emissions. For example, many paper finishes that are applied to raw engineered wood are impregnated with resins; these resins are added during the paper making process to make the paper more durable. In addition, many papers and other types of overlays are coated with materials, usually resins, to give them a protective finish. Thus, an evaluation and understanding of the indoor air emissions associated with finishing materials is a critical step in the development and evaluation of pollution prevention opportunities such as low-emitting materials.

2.1 Resins Used to Manufacture Engineered Wood

Both the resins and the wood used to manufacture engineered wood products are sources of organic emissions. Urea-formaldehyde resins are the most commonly used adhesives for engineered wood manufacture in the United States. One of the major disadvantages of urea-formaldehyde resins is their susceptibility to hydrolytic degradation in the presence of moisture and/or acids. Hydrolysis of UF resins occurs when resins are exposed to water or to humid conditions. The resins absorb moisture resulting in the slow release of formaldehyde from

UF resins. The hydrolysis reaction mechanism is essentially the reverse reaction of the UF resin formation reaction (NRC, 1981).

Phenol-formaldehyde (PF) resins are the second most commonly used resin. Phenolic resins are used because of their desirable physical and chemical properties; they resist hydrolysis. Phenolic resins are relatively inexpensive compared to alternative resins, such as melamine, but they are more costly than urea-formaldehyde resins.

Methylenediphenyl diisocyanate (MDI) resins are the third most commonly used type in the United States. MDI is used in the production of approximately one third of the U.S. market of OSB and in the manufacture of other specialty products. The other two thirds of the U.S. production of OSB is made with PF resins. Currently, MDI binders are used in at least 18 OSB facilities in North America. In the United States, MDI binders are used to produce engineered structural lumber products and MDF. MDF produced with MDI binders is used to make exterior-grade products and low-formaldehyde-emitting interior-grade products. In Europe, MDI binders are used to produce both PB and MDF, resulting in a reduction of formaldehyde emissions from the finished panel (ICI, personal communication, 1994). Products made with MDI emit little formaldehyde (Meyer et al., 1986). When compared with the other three resins discussed, MDI has adhesive properties equivalent to, if not better than, phenolic formaldehyde resins, and its water resistance is superior (Meyer, 1979). Higher price, the tendency of the adhesive to adhere to manufacturing equipment, and worker exposure issues have limited MDI applications. These adhesives are expensive and require expensive manufacturing processes (Meyer et al., 1986).

Melamine-formaldehyde resins are used extensively in Europe and Scandinavia, mainly to produce exterior board products and interior-grade products that meet European indoor emissions standards. Melamine resins are well established in the European market and have been popular in producing interior-grade plywood. Melamine products emit more formaldehyde than phenolic resins but significantly less than UF products (Meyer, 1979).

Resorcinol-formaldehyde resins are waterproof and form the strongest wood bond of the previously mentioned formaldehyde-based resins (Pizzi, 1983); however, they are the most expensive (Pizzi, 1983; Sellers et al., 1988). Resorcinol-formaldehyde resins are the most durable and strongest of the four formaldehyde resins mentioned (Koch et al., 1987). They are often described as the “ideal adhesive” due to their durable, waterproof bonding and short curing times at ambient temperature (Koch et al., 1987); however, resorcinol-formaldehyde resins are very expensive (\$1.45 per pound in 1985 dollars). To obtain some of the quality of a resorcinol resin at a lower cost, phenol-resorcinol-formaldehyde (PRF) resins have been developed. These highly durable resins are produced by combining phenol with formaldehyde under mildly alkaline conditions, followed by a resorcinol addition and completion of the synthesis (Sellers et al., 1988).

Often, more expensive formaldehyde-based resins, such as melamine- and resorcinol-formaldehyde resins, are blended with other formaldehyde-based resins (Koch et al., 1987;

Blomquist et al., 1981). Melamine-urea-formaldehyde and phenol-resorcinol-formaldehyde are two examples of these blended systems. These are combined to provide improved performance using the advantageous properties of each constituent in the system (Koch et al., 1987; Blomquist et al., 1981) while reducing expense. Melamine-formaldehyde resins (Meyer et al., 1986), melamine-urea-formaldehyde resins, PF resins, and MDI are used largely in the European engineered wood markets (WPPF, 1994). Table 2-1 shows typical applications and mixed cost per pound for some of these resins, and a discussion of the chemistry of each of these resinous products is provided in Appendix A.

2.2 Finishing Materials

Types of finishing materials used on engineered wood materials include laminates, edge-bands, adhesives for attaching laminates and edge-bands, conversion varnish coatings, paints, stains, fire retardants, and preservatives. Some of these finishing materials are sources of organic emissions while others, such as laminates or veneers, may help reduce emissions (the usefulness of laminates and veneers for reducing emissions is discussed in Section 6.3.2). Appendix B presents summaries of several studies of indoor emissions associated with finished and unfinished engineered wood materials made with various resins.

2.3 Emissions Rates

In 1984, the Department of Housing and Urban Development (HUD) established formaldehyde product standards for plywood and PB materials bonded with a resin system or coated with a surface finish containing formaldehyde when installed in manufactured homes* (*Federal Register*, 1984). Many plywood and PB manufacturers changed their products to comply. Most of this section focuses on recent indoor air studies and presents studies that evaluate various sources of indoor air emissions and how the emissions rates are affected by various parameters.[†] Appendix B presents emissions rate information from several studies, and Section 2.4 presents the effects of several physical parameters, such as temperature and humidity, on indoor air emissions from engineered wood products.

One study, presented in Appendix B, concluded that new building materials produced high emissions levels, but with effective ventilation (the ventilation rate was 2.5 air changes per hour)

* The HUD safety standards (24 CFR 3280.308) for certified plywood and PB used in manufactured home construction require that formaldehyde emissions not exceed 0.2 ppm (0.246 mg/m³) from plywood and 0.3 ppm (0.369 mg/m³) for PB, as measured by the specified air chamber test. The specified air chamber test is the Large-Scale Test Method FTM 2-1983. Individual engineered wood products are tested in accordance with the following loading ratios: plywood--0.29 ft³/ft³ (or 0.369 m³/m³) and PB--0.13 ft³/ft³ (or 0.43 m³/m³) (24 CFR 3280.406). Using the operation conditions specified in the Large-Scale Test Method FTM 2-1983 and the formaldehyde emissions rate equation, formaldehyde emissions rates are 0.13 mg/m² • h (2.66 x 10⁻⁸ lb/ft² • h) for plywood and 0.43 mg/m² • h (8.81 x 10⁻⁸ lb/ft² • h) for PB.

[†] The reader is referred to Godish (1988) for an evaluation of additional indoor air studies performed before 1984.

Table 2-1. Commonly Used Adhesives

Adhesive Resin	Typical Application	Mixed Cost/lb ^a
Urea-formaldehyde	HW flooring, Type II plywood (decorative), PB, and fiberboard; interior exposure; furniture; wood veneering	0.08
Phenol-formaldehyde	Structural plywood, truss components, PB, OSB, and WB; exterior exposure; boat building; furniture	0.10 (plywood)
		0.34 (OSB, liquid)
		0.55 (WB, spray-dried)
Melamine/Urea-formaldehyde	Plywood (decorative), flat-bed stock, and end joints in laminating; interior and limited exterior exposure; furniture	0.30
Isocyanates	WB, OSB, and PB; interior and exterior exposure	0.70
Melamine-formaldehyde	Laminated beams (moderate in use in U.S.), end joints in laminating truck decking, and Type I HW plywood (decorative); limited exterior exposure	0.40
Phenol-resorcinol formaldehyde	Bridge and pier components, boat building, laminated beams, and truck decking; interior and exterior exposure	1.30
Resorcinol-formaldehyde	Laminates, ship components, outdoor furniture, and fire-rated panels; extreme exterior service	1.45

Sources: Sellers et al., 1988; Pizzi, 1983.

HW = Hardwood.

OSB = Oriented strandboard.

PB = Particleboard.

WB = Waferboard.

^a In 1985 dollars.

these emissions could be reduced. This study covered measurements taken for an 8-month period (Saarela and Mattinen, 1993). The maximum concentration of formaldehyde reached 0.122 mg/m^3 in the new office building investigated for the Saarela study. Another indoor analysis suggested that building materials may be the main source of organic compounds in the indoor environment (Mølhave, 1982). The total average concentration for the most frequently identified compounds in this study was $72.96 \text{ } \mu\text{g/m}^3$, and the average arithmetic mean emissions rate for all the identified compounds was $9.5 \text{ mg/m}^2 \cdot \text{h}$ (Mølhave, 1982). The Levin et al., study (1989) presented predicted emissions rates, and the Meyer study (1983) presented emissions rate ranges for several engineered wood products. The remaining studies analyzed samples of various engineered wood products (Sundin, 1992; GTRI, 1993; GEOMET, 1994; Thøgersen et al., 1993). The National Particleboard Association (NPA) had a two-part preliminary study conducted by two laboratories, GEOMET Technologies and Georgia Tech Research Institute. The GEOMET study (1994) analyzed emissions from finished and unfinished engineered wood products. For most of the finished samples of Southern Yellow Pine (SYP) substrates, the total volatile organic compounds (TVOC) concentrations (with ranges from $156 \text{ } \mu\text{g/m}^3$ at 24 hours to $2,520 \text{ } \mu\text{g/m}^3$ at 120 hours) were lower than unfinished SYP substrates (with ranges of $2,880 \text{ } \mu\text{g/m}^3$ at 24 hours to $918 \text{ } \mu\text{g/m}^3$ at 120 hours). The results of these analyses are presented in Appendix B. In addition to measuring organic emissions for water-damaged chipboard, which had a mean formaldehyde concentration of about 0.0475 mg/m^3 , the Thøgersen et al. study (1993) evaluated microbiological growth from water-damaged chipboard samples and revealed significant growth of fungi following water damage. Although not discussed in Appendix B, EPA performed earlier research on a variety of consumer products and building materials that presented emissions rate data and discussed the effect of temperature and air exchange on the emissions rate (Tichenor and Mason, 1988).

Reported information concerning organic and formaldehyde emissions rates and concentrations was dependent upon the design and objectives of each study. Emissions data for each individual study were collected using different analytical test methods. Because methods used to collect emissions data were study-dependent and researchers presented emissions data differently, comparative conclusions could not be drawn between the studies presented in this report.

2.4 Effects of Physical Parameters on Emissions

The indoor environment is not static. Temperature, humidity, and air exchange rates vary continually over the course of a day, from day to day, and seasonally. These environmental variations influence indoor concentrations. In addition, many other parameters affect indoor concentrations, including types and quantities of materials used in construction and furnishing, volume-to-surface ratio of those materials, kind and method of air control (ventilation), indoor activities, and structural tightness of energy-efficient buildings.

Formaldehyde emissions from engineered wood increase with increasing temperatures and decrease with decreasing temperatures. Formaldehyde emissions are sensitive to absolute and relative humidity. Diurnal variations of formaldehyde concentrations coincide well with changes

in indoor temperature. Emissions are highest during summer months when temperature is high, and emissions are lowest during winter months when temperature is low. Formaldehyde emissions also correlate linearly with average ambient temperatures under controlled indoor environmental conditions. Outdoor temperature changes alter the pressure differences between the inside and outside of the structure. These pressure differences are one major factor contributing to air infiltration into the indoor environment. Formaldehyde concentrations are significantly affected by ventilation. When indoor temperature and humidity are held constant, formaldehyde concentrations will be higher under closure conditions than when windows and doors are open (Godish, 1988). Little information is available on the effects of physical parameters on nonformaldehyde emissions.

When wood is exposed to air in which the humidity is variable, it changes in moisture content and shrinks or swells accordingly. Engineered wood materials made with UF are not water resistant and consequently can absorb water. This absorbed water can act in two ways: (1) it can react with free formaldehyde present in the wood from incomplete cross-linking of the UF resin; and (2) it can cause slow hydrolysis of the UF resin, resulting in a slow release of formaldehyde.

2.5 Health Effects Related to Indoor Air Quality

A multitude of organic compounds with a high degree of variability and relative concentrations found from one microenvironment to another characterize the indoor air environment. The effort required to evaluate each possible indoor microenvironment and each possible indoor air pollutant is prohibitive. As a result, TVOC has become a measurement of exposure and indoor air quality complaints. Many studies have attempted to correlate indoor TVOC levels with indoor air complaints, and to use TVOC as a measure for acceptable indoor air quality.

Formaldehyde is one of the most studied organic compounds regarding toxicity. It has been shown to have a wide range of effects in both humans and experimental animal species. The EPA has classified formaldehyde as a "Probable Human Carcinogen" (Group B1) following its guidelines for carcinogenic risk assessment (U.S. EPA, 1994). Available epidemiologic data suggest limited evidence for carcinogenicity in humans; however, sufficient evidence of genotoxicity and carcinogenicity in experimental animals supported these data. Formaldehyde has also been associated with eye and nose irritation, changes in respiratory function, and respiratory irritation. A thorough evaluation of the health and environmental effects was beyond the scope of this project.

3.0 ENGINEERED WOOD PRODUCT CLASSIFICATIONS AND INDUSTRY STATISTICS

Engineered wood products are distinct from solid wood in that they are composed of wooden elements of varying sizes held together by an adhesive bond (Table 3-1). In general, the manufacturing process involves some type of wood size reduction, followed by drying (except for wet process boards), adhesive application, and pressing at elevated temperatures.

Table 3-1. Engineered Wood Products

Product Type	Wood Form after Size Reduction	Primary Adhesive(s)	Manufacturing Process
Plywood panels			
-Structural plywood	Veneer	PF	Dry
-Hardwood plywood	Veneer	UF	Dry
Engineered lumber	Veneer and lumber	PF	Dry
Reconstituted wood panels			
-Oriented strandboard	Wood strands of uniform size	PF, MDI	Dry
-Particleboard	Finely ground wood particles of various sizes (fluffy, dust-like texture)	UF	Dry
-Medium-density fiberboard	Wood fibers of uniform size (fluffy, dust-like texture)	UF	Dry
-Cellulosic fiberboard	Wood fiber of uniform size (fluffy, dust-like texture)	Starch or asphalt	Wet
-Hardboard	Wood fibers of uniform size (fluffy, dust-like texture)	PF	Dry, wet, or wet/dry

PF=Phenol-Formaldehyde.

UF=Urea-Formaldehyde.

MDI=Methylenediphenyl diisocyanate.

3.1 Plywood Panels

Engineered wood panels made with wood veneers are classified as plywood. Veneer is produced by cutting or peeling thin sheets of wood from a log. In plywood manufacture, veneers are bonded together with a synthetic adhesive resin to form a laminate. (A laminate is any object built up of thin layers.) The number of veneers or plies in a panel varies by product. The outside plies of a plywood panel are called the face and back. The center ply or plies are called cores. The center plies are layered with the grain of each sheet perpendicular to the previous one. Plywood may be made entirely of veneer, or the core materials may be lumber, PB, plastic, metal, or other materials (Figure 3-1).

Plywood panels are classified into two groups according to end use: structural plywood and hardwood plywood. Structural plywood panels are used primarily as a sheathing product in the construction of residential homes and nonresidential buildings; other applications include materials handling, concrete forming, and construction of transportation equipment, furniture, and fixtures. Hardwood plywood is used for decorative applications such as wall paneling and industrial applications such as furniture manufacture. The structural plywood industry is significantly larger than the hardwood plywood industry (Figure 3-2).

3.1.1 Structural Plywood

Structural plywood panels are made primarily from softwoods. Softwoods are coniferous or needle-leaved trees (pine, fir, spruce, hemlock), as opposed to hardwoods, which are deciduous or broad-leaved trees (oak, ash, maple, walnut). The term “softwood” has only a general reference to actual wood hardness. Structural panels may use either variety, but are more commonly manufactured of softwoods (APA, 1993).

Structural plywood panels are constructed entirely of veneers (typically 1/10 inch thick) that are bonded with PF adhesive resins. Phenol formaldehyde resins are waterproof, which allows structural panels to be used in exterior applications. Panels are typically manufactured into 4- by 8-foot sheets that may be sanded. No finishes (e.g., liquid coatings, paper coatings) are applied to the panels.

3.1.1.1 Industry Outlook

Since the mid-1980s, timber harvests from publicly owned lands have declined by more than 50 percent (Carliner, 1994). Industry attributes the decline to new land management policies by the Federal Government that have reduced the amount of land available for harvesting. Heavy restrictions have been placed on national forests in the Pacific Northwest that contain twice as much timber as all the other national forests combined (*Evergreen Magazine*, 1994).

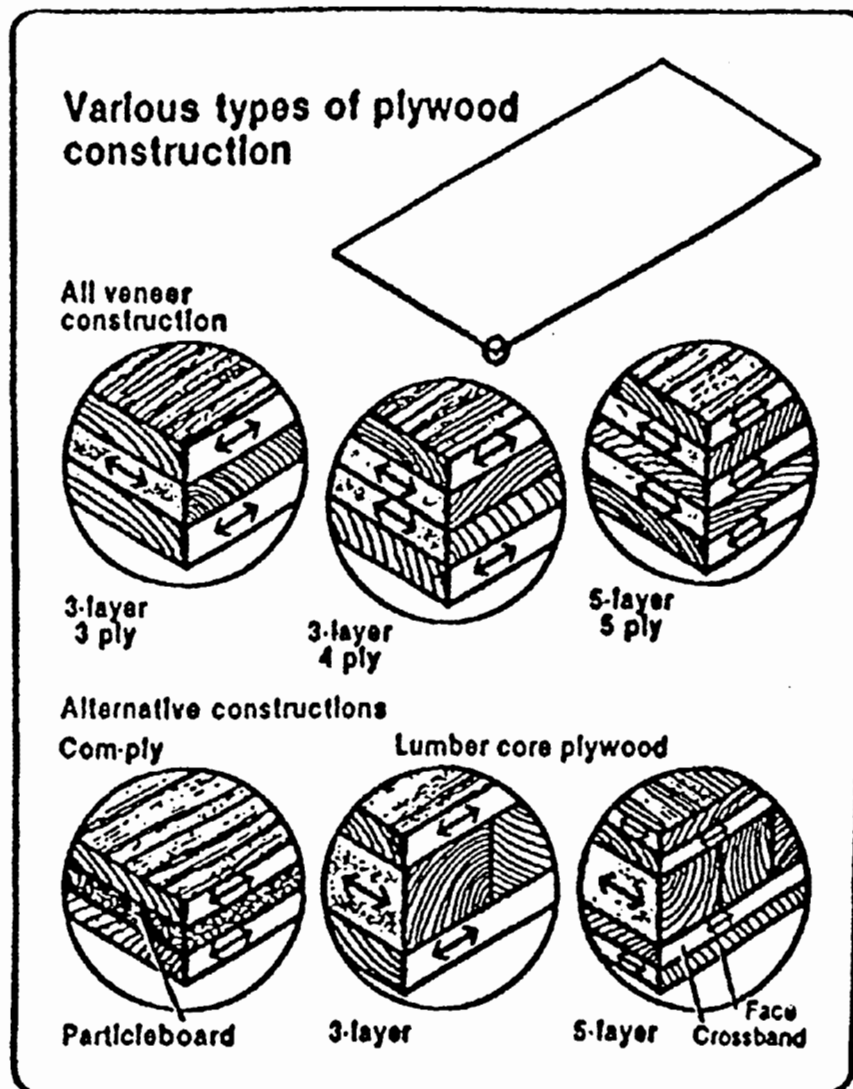


Figure 3-1. Various types of plywood construction (Haygreen and Bowyer, 1989).
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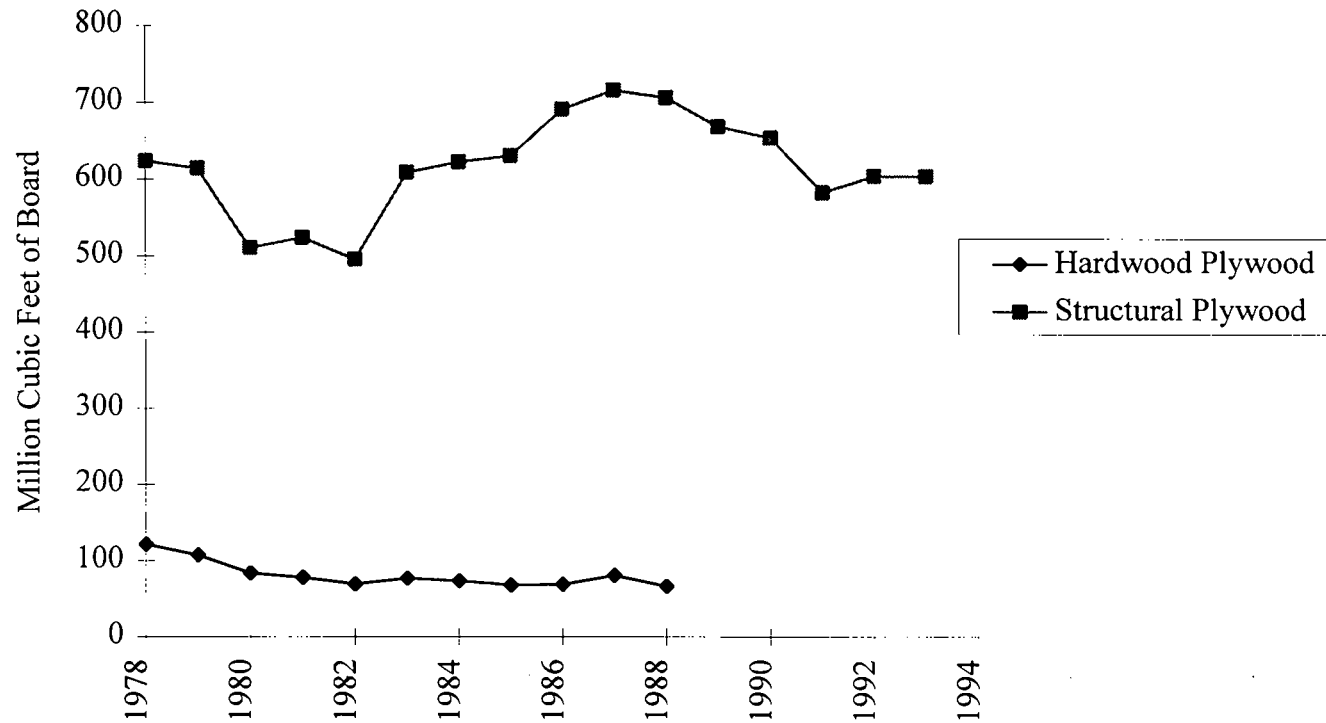


Figure 3-2. U.S. shipments of hardwood plywood and structural plywood(USDC, 1988; APA, 1993).

Notes

1. Data unavailable on shipments of hardwood plywood after 1988
2. Hardwood plywood data are reported as square feet of surface measure, irrespective of panel width. The pre mix of hardwood plywood panels ranges from 5/16 " to 3/8" in width (Groah, 1994); therefore, an average width o 11/32" was used to convert surface measure to cubic feet.

Harvesting restrictions have negatively impacted the structural plywood industry. The shortage of timber has increased log prices, resulting in increased manufacturing costs for plywood production. Rising lumber prices throughout the 1990s have also resulted in higher log costs. Lumber and plywood operations now compete for the same log. While plywood prices are held in check by substitution of oriented strandboard (see Section 3.3.2), lumber prices are more free to rise because there are fewer substitutes for lumber. The replacement of structural lumber is only in the beginning stages with products such as laminated veneer lumber (LVL) and glulam beams (see Section 3.2). Plywood is therefore less able to compete with lumber as a common log resource (Roberts, 1994).

The combination of log shortages, rising manufacturing costs, and competition from OSB have resulted in plywood production curtailments and mill closures, particularly in the West. There have been 112 plywood and veneer plant closures in Washington, Oregon, and California between 1980 and the end of 1993 (*Wood Technology*, 1994). Shipments of structural plywood from the West have decreased 53 percent since 1987 (Figure 3-3). Total U.S. shipments of structural plywood have decreased 15 percent since 1987.

3.1.2 Hardwood Plywood

Hardwood plywood is categorized into two types of products: prefinished wall paneling and industrial hardwood plywood. Prefinished wall paneling is bonded with UF adhesive resins, which are nonwaterproof. Industrial hardwood plywood is bonded with either UF or PF adhesive resins, depending on the end use application (i.e., PF adhesive resins are used where the bond must be waterproof).

3.1.2.1 Wall Paneling

Hardwood plywood wall panels are primarily 3-ply and 1/9 inch to 1/4 inch thick. All wall panels are prefinished. There are two types of prefinished wall paneling: (1) natural finished wall paneling and (2) decorative finished wall paneling. Plywood used for natural finished wall paneling is constructed in the United States from species such as oak, birch, walnut, elm, cherry, and pecan and is finished to retain its natural look. Plywood panels used for decorative finished wall paneling are imported from Indonesia. The imported panels are unfinished and are decorated (e.g., painted, laminated, etc.) in the United States.

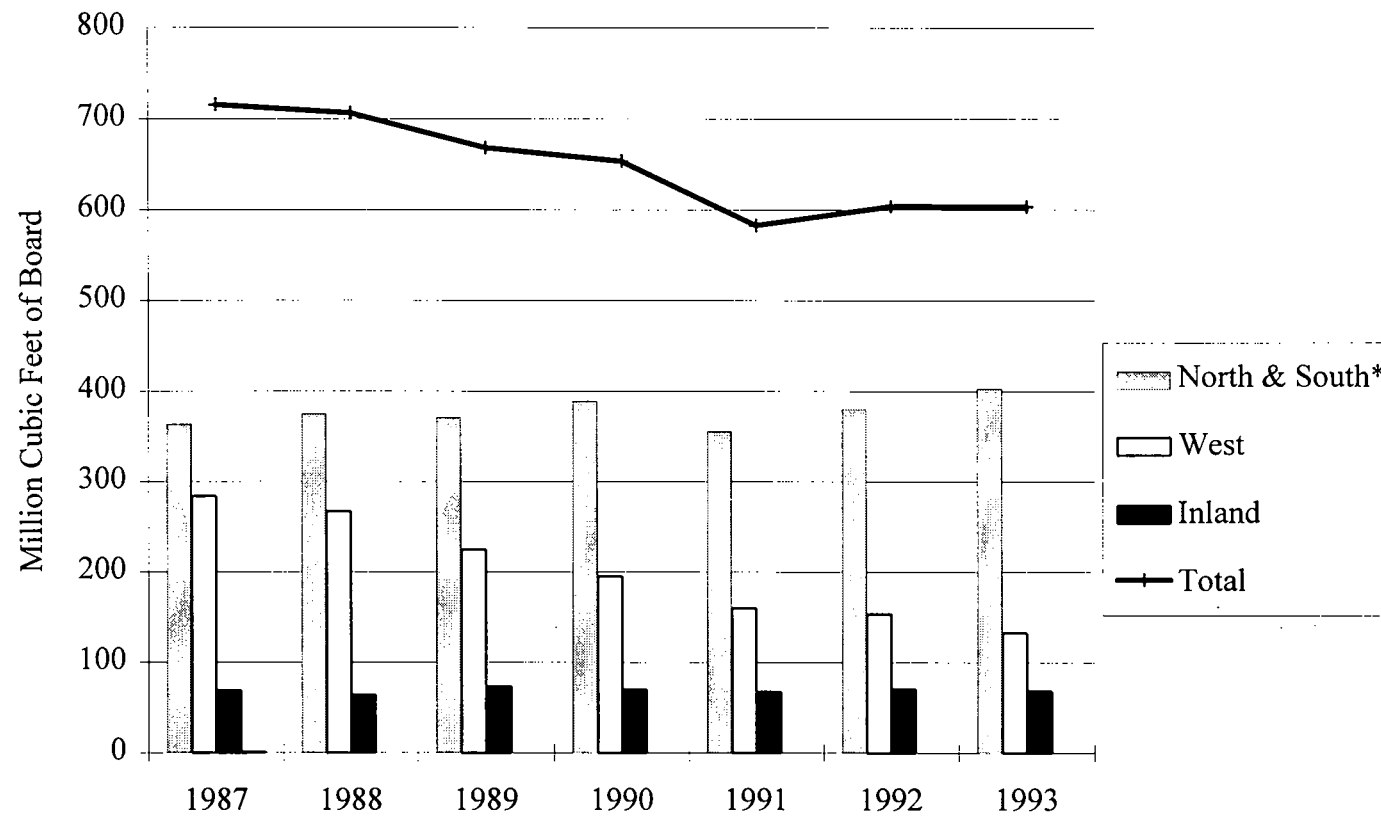


Figure 3-3. U.S. shipments of structural plywood 1987 to 1993 (APA, 1993).

*Shipments from the North are very small and were combined with shipments from the South to avoid disclosure

Industry Outlook. There has been a substantial decline in the use of prefinished wall paneling since the late 1970s. The total U.S. market for prefinished wall paneling has declined from around 110 million cubic feet in 1978 to 35 million cubic feet in 1992 (Figure 3-4). According to the Hardwood Plywood and Veneer Association (HPVA), the loss of market share by hardwood plywood wall paneling is due to the following factors:

- Customer preference for products such as gypsum wallboard that can be repainted (in different colors, if desired) so that the appearance of a room can be more easily changed from time to time (HPVA, 1991).
- The establishment of an Indonesian cartel, which has resulted in significant increases in the price of imported hardwood plywood blanks during the late 1970s and 1980s. Currently, Japan and China are the largest markets for Indonesian plywood, with the United States a distant third (HPVA, 1991).
- A decline in promotion and advertising by some of the major manufacturers accompanied, in some cases, by their withdrawal from the hardwood plywood paneling market (HPVA, 1991).
- Formaldehyde release from wall paneling, either real or perceived (HPVA, 1991).

3.1.2.2 Industrial Hardwood Plywood

Industrial hardwood plywood panels are commonly made using 3, 5, and 7 plies. The panels vary in thicknesses; ½ inch and ¾ inch thick panels are common. Industrial hardwood plywood panels are unfinished, i.e., coatings, laminates, etc., are not applied (HPVA, 1991). The unfinished panels are used in the manufacture of furniture, cabinets, and specialty panels. Some hardwood plywood industrial panels are made with a PB core (15 percent of the market) or an MDF core (15 percent of the market). Veneer core (65 percent of the market) is the predominant type used in industrial panels (HPVA, 1991). Unlike wall panels, production of industrial hardwood plywood panels has remained fairly constant over the years (Figure 3-5).

3.2 Engineered Lumber

As mentioned in Section 3.1.1.1, glulams beams and LVL are emerging as substitutes to lumber. Glulam is short for glued-laminated structural timber -- large beams fabricated by bonding layers of specially selected lumber with PF adhesives. End and edge jointing permit production of longer and wider structural wood members than are naturally available. Glulam timbers are used with structural wood panels for many types of heavy timber construction.

Laminated veneer lumber is constructed of veneers that are bonded together with a PF adhesive resin to form a laminate; the veneers are layered with the wood grain along the long axis of the beam. The thickness of the veneers varies from 1-3/8 inches to 1-1/2 inches. Laminated veneer

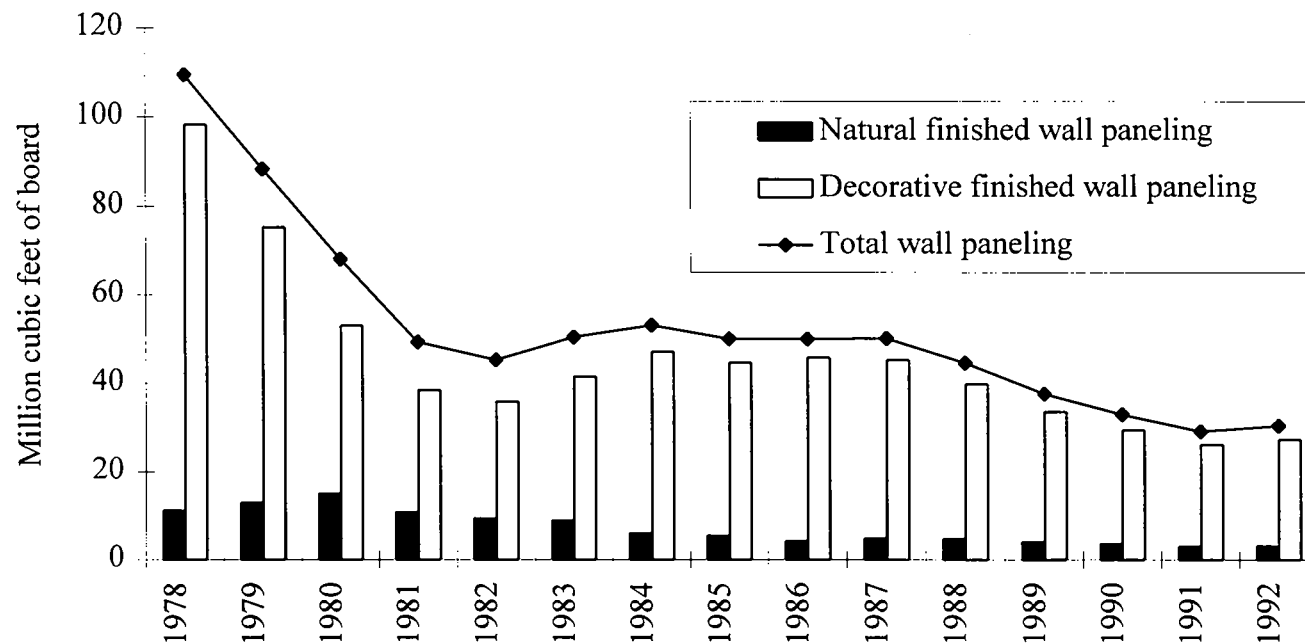


Figure 3-4. U.S. production of hardwood plywood wall paneling (Groah, 1999)

Notes:

1. Shipments of hardwood plywood are reported as sq. ft of surface measure, irrespective of panel thickness. The present hardwood plywood panels range in thickness from 0.313 in to 0.375 in (Groah, 1994). An average thickness of 0.344 in is used to convert surface measure to cubic feet.

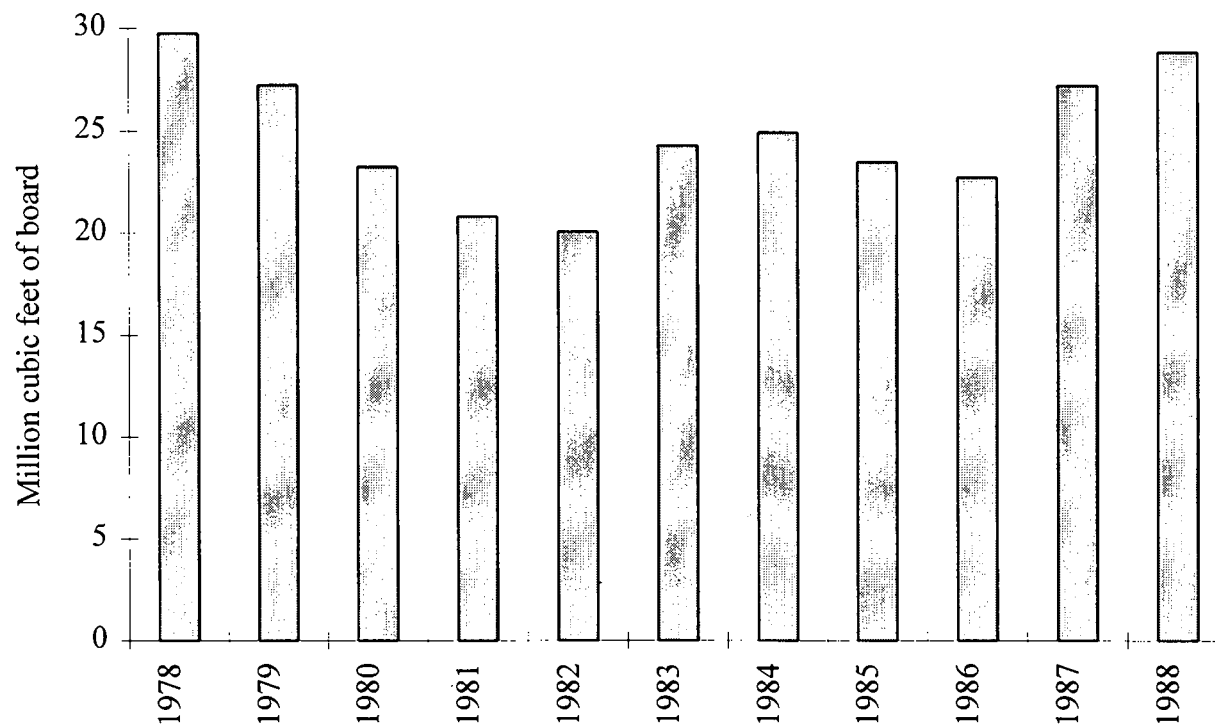


Figure 3-5. U.S. shipments of industrial hardwood plywood (USDC, 1988).

Notes:

1. Shipments of hardwood plywood are reported as sq. ft of surface measure, irrespective of panel thickness. The present mix of hardwood plywood panels ranges in thickness from 0.313 in to 0.375 in (Groah, 1994). An average thickness of 0.344 in was used to convert surface measure to cubic feet.

lumber is manufactured to typical lumber sizes (2 by 4, 2 by 6, etc.). The beams can be manufactured up to 30 feet long using end joints or finger joints. Another application of LVL is in the construction of wood I-joists. (An I-joist is a small beam that resembles the letter "I".) Laminated veneer lumber is used to construct the top and bottom of the joist and OSB is used to construct the center.

3.2.1 Industry Outlook

As seen in Table 3-2, the production of glulam beams and LVL is increasing rapidly and is expected to continue. By 2003, the North American output of LVL is expected to reach 98 million cubic feet (Blackman, 1994).

Table 3-2. U.S. Production Estimates of Engineered Lumber^a

	1992	1993	1994	1995	1996	1997
Glulam beams (million board feet)	271	288	308	352	392	391
I-joists (million linear feet)	225	350	385	440	495	450
Laminated veneer lumber (million cubic feet)	18	25	29	33	39	37

Source: APA, 1993.

^aProduction figures for 1993-1997 are estimated.

3.3 Reconstituted Wood Panels

Engineered wood panels made with wood strands, particles, and fibers are classified as reconstituted wood panels. Reconstituted wood panels include PB, OSB, cellulosic fiberboard, MDF, and hardboard. Table 3-3 lists shipments of reconstituted wood panels by U.S. manufacturers on a volume basis (cubic feet of board) from 1985 to 1993. Particleboard, OSB, and MDF represented 84 percent of reconstituted panel shipments by U.S. manufacturers in 1993.

3.3.1 Particleboard

Particleboard is a panel product made from finely ground wood particles of various sizes that are bonded together with a synthetic adhesive resin under heat and pressure in a hot press. Other materials may also be added during manufacturing to improve certain properties such as fire resistance and dimensional stability. The wood particles come primarily from planer shavings, sawdust, plywood trimmings, and other process residuals. Most PB in the United States is bonded with UF adhesive resins. Particleboard panels bonded with UF adhesive resins are used for interior applications that do not require water resistant materials.

Table 3-3. U.S. Shipments of Reconstituted Wood Panel (million ft³) 1985 to 1993

	PB	OSB	MDF	Hardboard	Cellulosic Fiberboard
1983	188	42	38	NA	NA
1984	200	64	40	NA	NA
1985	208	83	43	66	NA
1986	225	110	49	61	NA
1987	232	127	56	57	49
1988	239	144	59	53	49
1989	241	160	61	54	50
1990	238	169	59	52	51
1991	236	175	60	51	47
1992	249	208	67	55	54
1993	265	219	101	55	54

Source: NPA, 1994b; AFA, 1994.

NA = Not available

Particleboard panels are manufactured in a variety of sizes and densities, depending on the specific end use application. Panel sizes range from 3 to 9 feet in width, ¼ inch to 2 inches in thickness, and almost any length that is transportable. Particleboard panels are used for industrial applications, floor underlay, mobile home decking, door core, shelving, and stair treads. The most common use of PB panels is for industrial applications. Industrial-grade panels represented 80 percent of PB shipments by U.S. manufacturers in 1993. In comparison, PB used for floor underlay made up 7 percent of the 1993 shipments, mobile home decking (4 percent), door core (3 percent), shelving (2 percent), and stair treads (0.3 percent). A large volume of industrial grade PB is used as a core stock material for furniture (domestic, institutional, office), kitchen and vanity cabinets (sides, backs, drawers, doors), doors (solid core flush doors, bifolds, sliding doors), games (table tennis, pool tables), and other goods. Industrial-grade PB is also used as a substrate for laminated panel construction such as countertops, desktops, wall paneling, and shelving. High-pressure laminates; thermofused, resin-saturated papers; vinyl films; hot transfer films; decorative papers; and wood veneers are the types of overlay materials most commonly applied to PB substrates (NPA, 1994a).

3.3.1.1 Industry Outlook

Shipments of industrial PB by U.S. manufacturers have been increasing steadily since the early 1980s and in 1993 were at record levels (Figure 3-6). Statistics for PB panels manufactured in the United States are compiled by the NPA. The NPA also compiles statistics for MDF panels manufactured in the United States. Statistics are compiled from member companies who

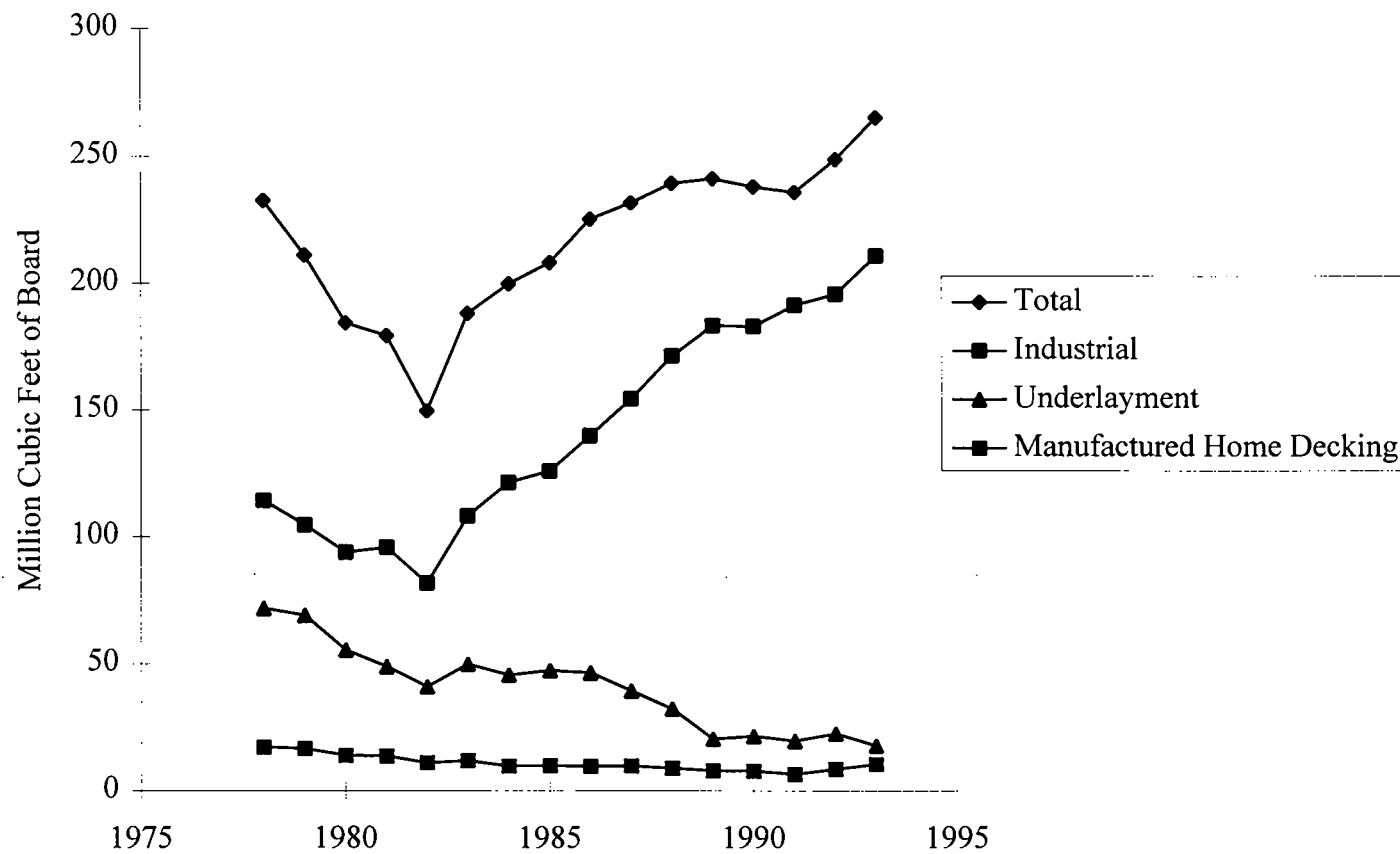


Figure 3-6. U.S. industry shipments of particleboard 1978 to 1993 (NPA 1994b)

represent more than 85 percent of the total U.S. manufacturing capacity for U.S. PB and MDF. Most of the PB manufactured by NPA members is unfinished, i.e., there are no coatings or laminates applied to the board at the plant; of the 265 million cubic feet of PB shipped in 1993, 3 percent was laminated and 1 percent was coated (NPA, 1994b). Particleboard is laminated and finished by end users such as furniture and cabinet manufacturers as well as producers in the laminating industry who sell finished PB to furniture and cabinet manufacturers.

3.3.2 Oriented Strandboard

Oriented strandboard is made from strands of wood bonded together with a waterproof adhesive under heat and pressure in a hot press. The strands of wood are sliced from small diameter, fast growing trees; tree species used are generally aspen in the northern U.S. and pine and soft hardwoods in the southern United States. Strand dimensions vary depending on the slicing machinery and wood species. Typical strand dimensions are 3 inches long, 3/16 to 2 inches wide, and 20/1000 to 28/1000 inches thick (about the thickness of a business card). The strands of wood in the surface layers are aligned in the long panel direction, while the inner layers are random or cross aligned. The OSB process was developed in the early 1980s as an improvement to the waferboard process in which strands of wood were randomly distributed throughout the panel. Two-thirds of the U.S. production of OSB is made with PF adhesives, and the remaining third is made with MDI adhesives.

Oriented strandboard is used in structural applications as a replacement for sheathing-grade plywood. The most common applications are for wall and roof sheathing and floor decking in wood frame construction. Other applications include materials handling (crates and pallets), web material for wood I-beams, siding, and other specialty products. The strength of OSB comes from the uninterrupted wood fiber, interleaving of the long strands, and degree of orientation of the strands in the surface layers. The waterproof adhesives combined with the strands provide internal strength, rigidity, and moisture resistance.

3.3.2.1 Industry Outlook

As illustrated in Figure 3-7, OSB has been rapidly increasing its share of the U.S. structural panel market. By late 1996, the capacity of OSB is expected to increase by 45 percent in the U.S. and by 130 percent in Canada; total North American capacity is expected to rise by 70 percent (Roberts, 1994). A key factor in the growing OSB demand is the continuing decline of structural plywood production. The substitution of OSB for structural plywood has been relatively easy since it competes on price at equal or near equal performance. In the future, the falling price of OSB due to new capacity will also play a key role in encouraging its substitution.

3.3.3 Hardboard

Hardboard is made with wood fibers bonded with a synthetic adhesive resin under heat and pressure with a waterproof adhesive. Phenol-formaldehyde adhesives are used to bind hardboard

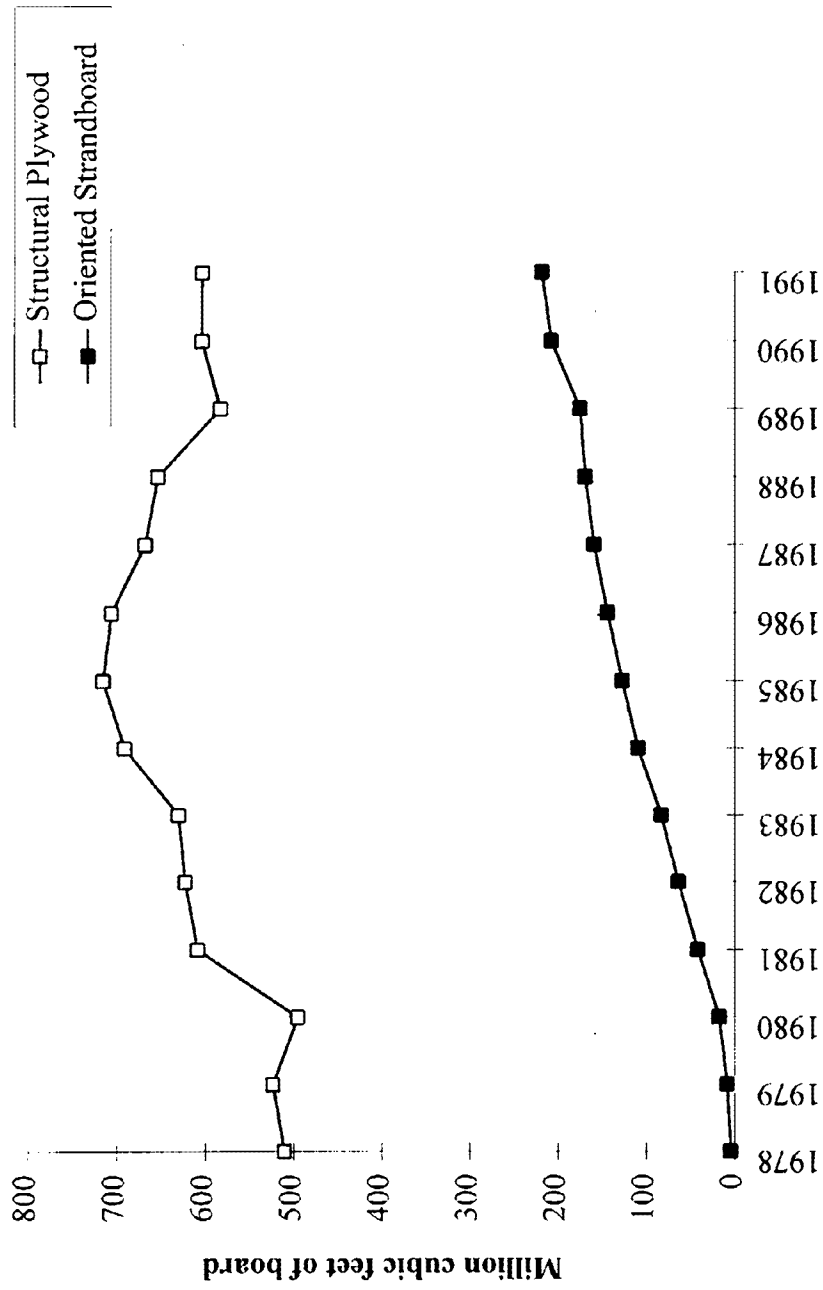


Figure 3-7. U.S. structural panel market (APA, 1993).

in the United States. Hardboard is manufactured by a wet, dry, or wet per dry process (see Section 4.2.5.1). Raw materials used to generate wood fibers in the dry hardboard process are primarily dry planer shavings from lumber operations. Green chips are used to generate wood fibers for wet and wet/dry hardboard processes (green means that the wood has never been dried). Most green chips are chipped from lumber slabs and forest harvesting residues, such as branches and tops. (In the lumber process, logs are peeled and then cut to length with squared sides; lumber slabs are the part of the tree that remains after the lumber has been cut.) A small amount of green chips are chipped from roundwood

Hardboard has a density ranging from 40 to 70 lb/ft³ and is categorized into three product groups: basic hardboard, hardboard siding, and prefinished wall paneling. Basic hardboard and siding make up the largest volume of hardboard products. Basic hardboard is used in a wide variety of applications including floor underlayment, furniture, case goods, truck and head liners, and door skins and faces; door skins and faces are the fastest growing market for basic hardboard (Wagner, 1994).

3.3.4 Medium-Density Fiberboard

Medium-density fiberboard is made with wood fibers bonded together with a synthetic adhesive resin under heat and pressure in a hot press. Urea-formaldehyde adhesive resins are the primary type of resin used to manufacture MDF in the United States. Raw materials used to generate the fibers come from dry planer shavings, plywood trim, and sawdust. The density of MDF ranges from 40 to 60 lb/ft³.

Medium-density fiberboard is used in the manufacture of furniture, cabinets, and general millwork applications. It is increasingly being used as a substitute for kiln-dried dressed lumber in applications such as window frames, door jambs, and decorative moldings. While nearly all MDF is made with non-water-resistant UF adhesives aimed at interior applications, there is continuing development and interest in exterior-grade panels and overlay systems that allow MDF panels to be used outside (Roberts, 1994). Due to the fine texture and homogeneous nature of MDF, it machines clean and is easily painted to produce high-quality finishes. Because MDF is made and sold as a panel, many furniture and cabinet components can be made from a single piece. The same components made from natural wood require labor intensive jointing and assembly operation.

3.3.4.1 Industry Outlook

The MDF industry is growing rapidly; U.S. shipments of MDF were at record levels in 1993 (Figure 3-8). The United States currently accounts for about 90 percent of North America's MDF capacity (Roberts, 1994). By late 1996, U.S. capacity is expected to increase by 30 percent, while Canadian capacity is expected to increase to over five times its current level; total North American capacity will rise by 75 percent (Roberts, 1994).

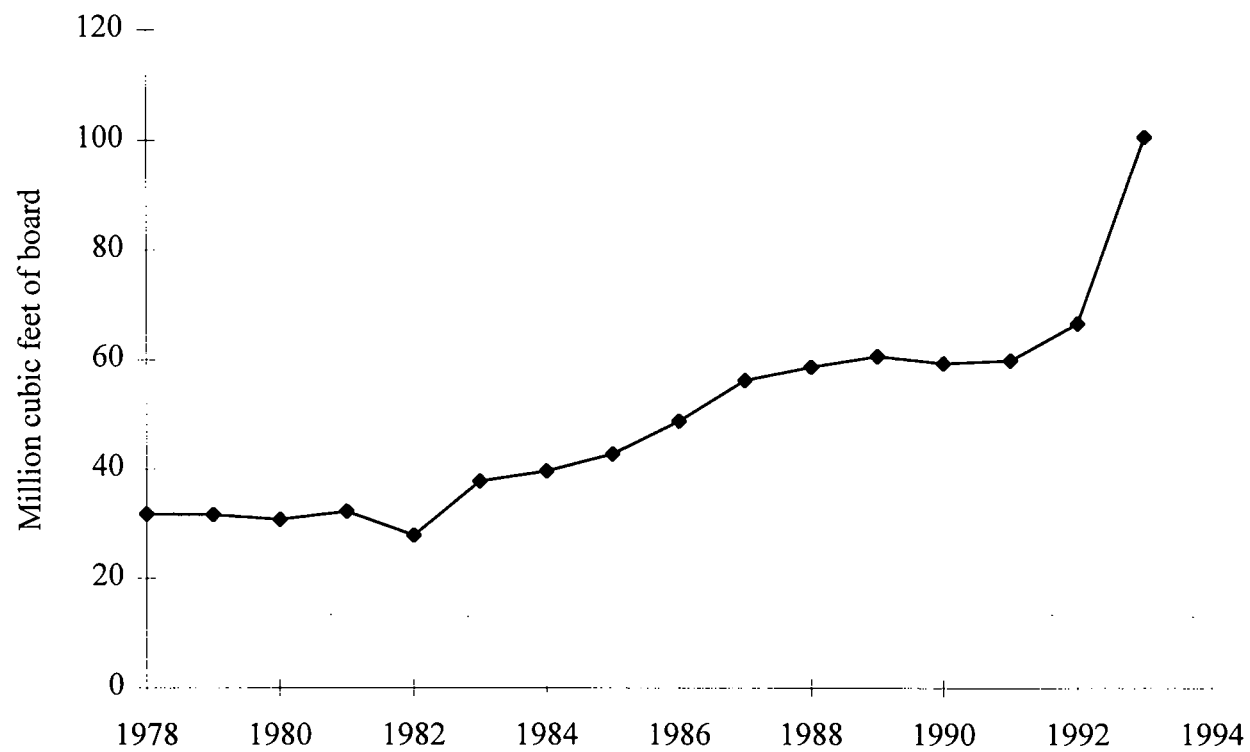


Figure 3-8. U.S. shipments of medium density fiberboard (NPA, 1994b).

3.3.5 Cellulosic Fiberboard

Cellulosic fiberboard is composed of wood fibers bonded together with either starch or asphalt. The raw materials used to generate the wood fibers are primarily green chips. A few plants in the U.S. manufacture cellulosic fiberboard from bagasse and newsprint. Cellulosic fiberboard is a low-density board ranging from 10 to 30 lb/ft³. Ninety percent of the 1993 shipments of cellulosic fiberboard were comprised of exterior wall sheathing, roofing, or other specialized exterior panels; the remaining 10 percent were used in a variety of industrial applications (Wagner, 1994).

4.0 ENGINEERED WOOD MANUFACTURING PROCESS DESCRIPTIONS

4.1 Plywood Manufacture**

The following sections describe the manufacturing processes involved in making plywood. The major steps include the following: debarking, heating the blocks, cutting veneer, drying veneer, lay-up and pressing, and finishing.

4.1.1 Debarking

The most widely used type of debarker in medium to large mills is the ring debarker. In this machine the log passes through a rotating ring that holds a number of pressure bars. These press against the log and tear off the bark. Large units of this type can debark logs at speeds of up to 200 lineal ft/min.

A rossing head type of debarker is sometimes used in mills where high production rates are not needed. The rossing head is a rotating cutterhead, similar to the head on a lumber planer, that rides along the log and cuts off the bark as the log is rotated. This debarker is also suited to situations where crooked or stubby logs must be debarked.

4.1.2 Heating the Blocks

When logs are cut to the length required for rotary veneer cutting, they are called blocks. Almost all hardwood and many softwood blocks are heated prior to cutting the veneer. Heating softens the wood and knots, making it easier to cut. It also improves surface quality, reducing roughness. Some of the dense hardwoods must be heated to produce satisfactory veneer. Softwood veneer from some species can be produced from cold logs because of their lower density and because the roughness limitations are less critical than for high-quality hardwoods. However, even in the softwood industry the advantages of heating the blocks generally outweigh the cost of the process. Baldwin (1975) lists four advantages of heating softwood logs:

** Sections 4.1.1 through 4.1.6 were reprinted with permission from *Forest Products and Wood Science: An Introduction* by J.A. Haygreen and J.L. Bowyer, Second Edition, Iowa State University Press, 1989.

1. Higher yields of veneer can be obtained from the logs. The reduction of cutting imperfections increases the yield an average of 3 - 5 percent.
2. The grade of the veneer is improved. Studies by Lutz (1960), Grantham and Atherton (1959), and the American Plywood Association (sic) have found that grades of veneer are upgraded from 4 to 25 percent.
3. Labor costs are reduced. Veneer from heated peeler blocks tends to hang together in a more continuous ribbon as it comes from the lathe. This reduces handling.
4. The amount of adhesive used can be reduced. Glue spreads can be lighter because of the improved surface.

A variety of methods are used to heat logs. Steaming, soaking in hot water, spraying with hot water, or combinations of these methods are all suitable to some situation. Dense hardwoods are usually heated by soaking at temperatures up to 200°F (93°C). Regardless of the heating medium, the objective is to heat the log to a suitable temperature as deeply into the log as veneer will be cut.

4.1.3 Cutting Veneer

Two major methods for producing veneer are slicing and peeling. Most veneer is produced by peeling (rotary cutting), which is accomplished on a veneer lathe. Slicing is used for producing decorative veneers from high-quality hardwood and is seldom used with softwoods. The cutting action on a lathe and on a slicer are very similar and are illustrated in Figure 4-1. In either case, the wood is forced under a pressure bar that slightly compresses the wood as it hits the cutting edge of the knife.

On the veneer slicer a cant of wood called the flitch is rigidly dogged, i.e., clamped, to a carriage that oscillates, cutting on the down stroke. Before each cutting stroke the knife and pressure bar move forward the thickness of the veneer to be cut. In a rotary lathe they move forward continuously as the block rotates.

4.1.4 Veneer Storage and Clipping

In modern mills the green veneer must be handled gently and rapidly as it comes from the lathe. The veneer is peeled at from 300 to 800 lineal ft/min. A series of trays is used in many softwood plywood plants to handle these long ribbons of wood. Trays are often about 120 ft long, long enough to handle the veneer that comes from a typical 15-in. block.

Clippers are high-speed knives that chop the veneer ribbons to usable widths. In hardwood veneer mills, clipping may be done manually to obtain the maximum amount of clear material from the flitch. In softwood mills and in some hardwood mills, clipping is often done automatically at speeds of up to 1500 lineal ft/min. The clipper will cut the veneer to about 54 in. (the panel width plus an allowance for shrinkage and panel trimming) if possible. However, if open defects are present, the veneer may be clipped to less than full panel width. Automatic clippers detect open defects with scanners that can be overridden by the operator when it is desirable to do so.

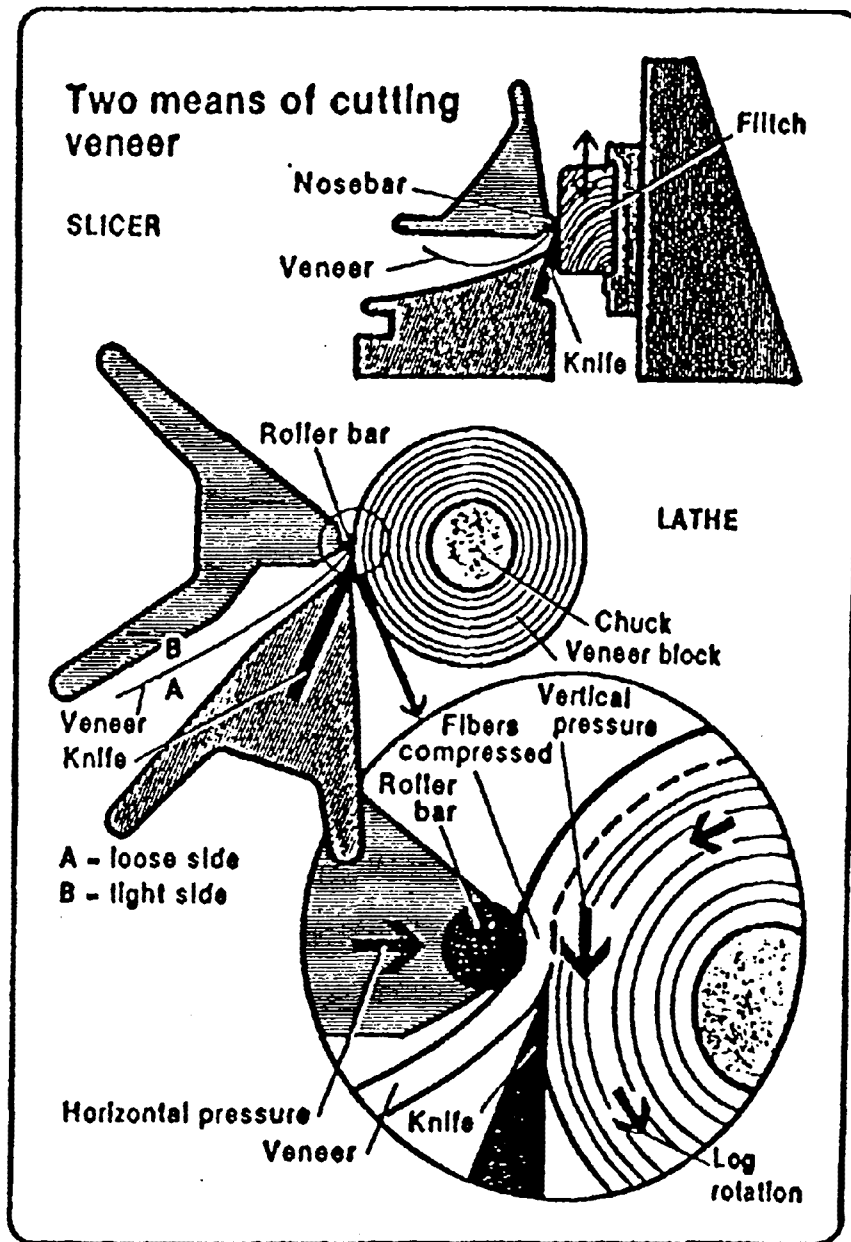


Figure 4-1. Cutting action on a lathe and slicer (Haygreen and Bowyer, 1989).
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4.1.5 Veneer Drying

Veneer driers consist of a means of conveying the veneer through a heated chamber where temperatures range from 150 to 260°C. In older roller driers, air is circulated in a manner similar to that in a dry kiln. This type of drier is still in wide use for hardwood veneer. Most plants built in recent years utilize jet driers. These are also called impingement driers since a curtain of air at velocities of 2000-4000 fpm is directed against the surface of veneer. The high velocity produces turbulent air on the surface of the veneer. This eliminates the laminar boundary that slows down heat and moisture transfer under ordinary drying conditions.

Developments such as the use of microwave energy, use of high temperature preheaters, and increased drying temperature (up to 800°F, or 427°C) may find use for some types of veneer drying. In most softwood veneers, however, temperatures over about 400°F (204°C) have adverse effects on glucability.

4.1.6 Lay-up and Pressing

Almost all adhesives used in the plywood industry in the United States today are thermosetting (cured by heat) synthetic resins. These have almost completely replaced the blood and soybean flour protein glues that were used in the past for interior (nonwaterproof) grades of plywood. The two most important types of resins used are phenol-formaldehyde, which is used for interior and exterior grades of softwood plywood and for exterior grades of hardwood plywood, and urea-formaldehyde, which is used to manufacture interior grades of hardwood plywood. The basic components of these resins are formaldehyde, which is derived from methanol, urea, and phenol.

Only rarely are pure or "neat" resins used as adhesives for plywood. In most cases they are mixed with fillers or extenders such as Furafile and fine flour produced from wood, bark, or nutshells. Furafile is a chemical lignocellulose by-product of furfuryl alcohol production that can be produced from corn cobs, rice hulls, and oat hulls. Starch and animal blood are also used as extenders to modify the viscosity, control the penetration into the wood, and control other characteristics of the adhesive mix such as the tack (stickiness).

The process of applying adhesives to the veneers, assembling veneers into a panel, and moving the panels in and out of the press are often the most labor-intensive steps in manufacture. Veneer is highly variable in width, length, and quality, which makes it a difficult material to handle with automated systems. Yet major advances have been made to increase automation in this stage of manufacture.

One advancement has been in the application of adhesive to the veneer. The old method is to pass veneer through rubber-faced grooved rollers that apply glue by contact to the top and bottom surfaces. One person is required to feed the roller glue spreader while an offbearer places the veneer onto the panel being laid up. If veneer is extremely rough, the glue spread will not be uniform and skips may occur.

Newer means of glue application, spray and curtain-coaters, have distinct advantages in terms of uniformity of the glue spread and are suited to automated lay-up systems. These methods overcome the problem of poor glue spread on rough stock. In these systems the veneers travel on a belt conveyor under the spray or curtain. A curtain-coater consists essentially of a box

with a slot in the bottom through which the adhesive flows in a continuous sheet or curtain. Glue not deposited on a piece of veneer passing through the curtain is pumped back up into the box.

Recently, two new methods of adhesive application, liquid extrusion and foamed resin extrusion, have been used successfully. These systems lay down continuous beads of resin on the veneer.

The actual assembly of veneer into plywood panels can also be mechanized — at least in larger plants producing standard-size panels. Although equipment has been developed to do this almost automatically, most mills use systems that are partially manual and partially mechanized. For example, the full-size 4 × 8-ft veneers for the two faces may be handled by machine, but the narrower strips of veneer used in the core may be assembled manually.

Most softwood plywood plants prepress the loads of laid-up panels prior to final pressing in the hot-press. This is done in a cold press at lower pressure. The purpose is to allow the wet adhesive to “tack” the veneer together. This permits easier loading of the hot-press and helps prevent shifting of the veneers during loading.

Pressing of the panels is usually done in the multiopening presses. Such presses can produce 20 - 40 4 × 8-ft panels at each pressing cycle, which may take 2 - 7 minutes. The purpose of the press is twofold: to bring the veneers into close contact so that the glue line is very thin and to heat the resin to the temperature required for the glue to polymerize. Adhesives made from phenol-formaldehyde resins typically require temperatures of 240°F (115.5°C) in the innermost glue line for approximately 90 seconds to cure properly. Resin systems must be carefully tailored to the specific conditions in a plant. Press time and temperature can be modified; i.e., a shorter press time may be possible if press temperature is increased.

4.1.7 Finishing

Stationary circular saws trim up to 1 inch from each side of the pressed plywood, producing even-edged sheets. About 20 percent of annual plywood production is sanded. Those that are sanded may be sanded on both sides or only one. Sheets move through enclosed automatic sanders while pneumatic collectors above and below the plywood continuously remove the sanderdust. Sawdust in trimming operations is also removed by pneumatic collectors. The plywood trim and sawdust are sold to reconstituted panel plants.

4.2 Reconstituted Panel Manufacture

The following sections describe the major processes involved in the manufacture of reconstituted wood panels. These processing steps include wood reduction, drying, adhesive blending, mat forming, and pressing (Figure 4-2). The drying and pressing steps are not required by all products.

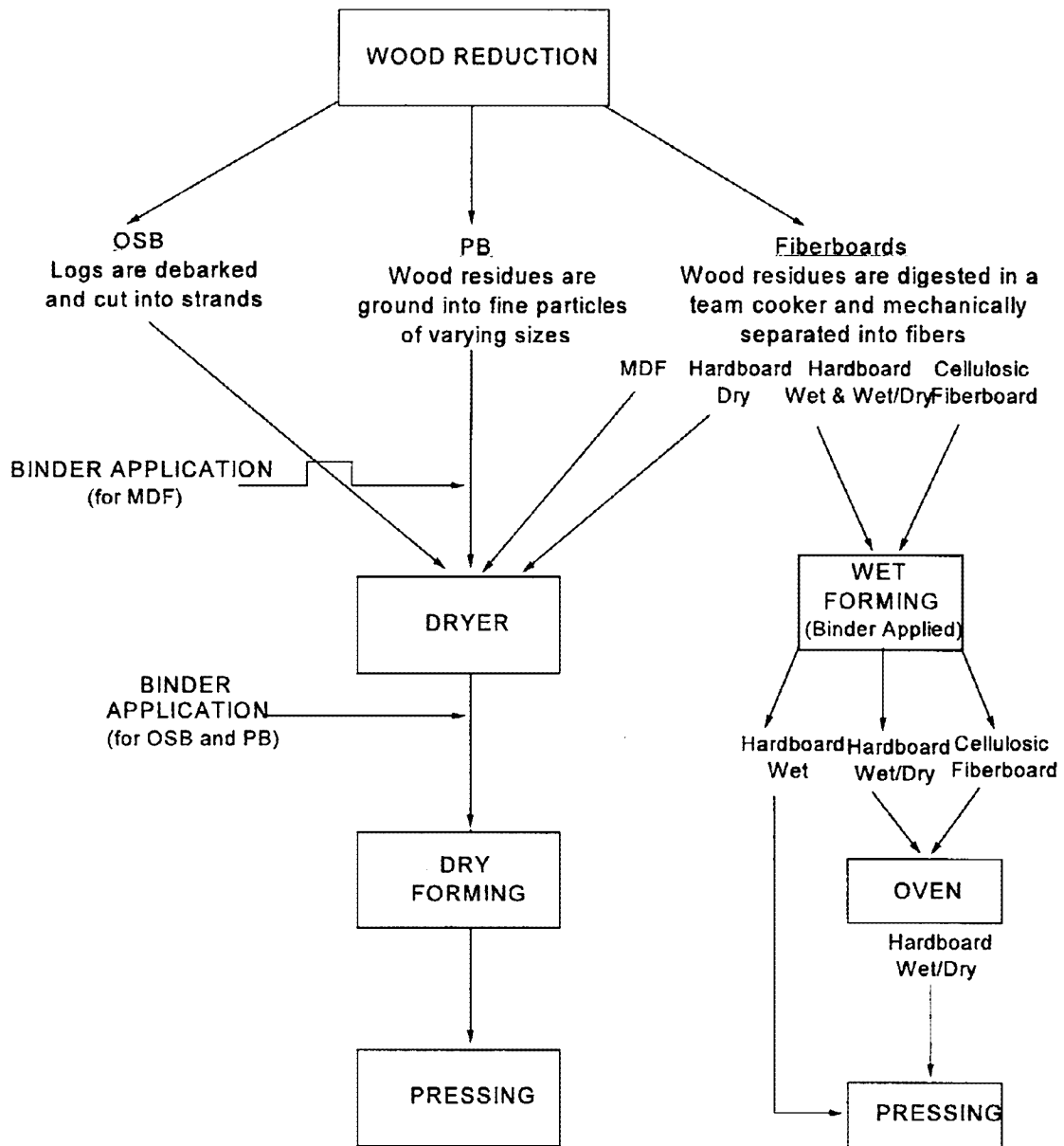


Figure 4-2. Reconstituted wood panel process flow.

4.2.1 Wood Reduction

4.2.1.1 Oriented Strandboard

The raw materials or “furnish” used to manufacture OSB are specially produced from green roundwood at the plant. Logs entering OSB plants are cut to 100-inch lengths by a slasher saw. The logs are debarked and carried to stationary slasher saws, where they are cut into 33-inch lengths called blocks. The blocks are then sent to a waferizer, which slices them into strands approximately 0.028 inches thick (Vaught, 1989). The strands are then conveyed to a storage bin to await processing through the dryers.

4.2.1.2 Particleboard

The furnish used to manufacture PB can be either green or dry process wood residues. Green process residues include planer shavings from surfacing green lumber, green sawdust, and plywood trim such as veneer clippings, edgings, and trimmings. Dry process residues include shavings from planing kiln-dried lumber, mill ends from kiln-dried lumber, sawdust, sanderdust and plywood trim. The wood residues are ground into particles of varying sizes using mechanical refiners and hammermills.

4.2.1.3 Fiberboard (Cellulosic Fiberboard, MDF, and Hardboard)

The furnish used to manufacture fiberboards consists of the same type of green or dry process wood residues used to manufacture PB. Fibers are generated by first cooking the wood residues in a moderate pressure steam vessel (digester). During this step the wood changes both chemically and physically; becoming less susceptible to the influences of moisture and less brittle as the lignin softens. This semiplastic wood is then “rubbed” apart into fiber bundles instead of being mechanically “broken” apart as in the PB process. The fibers are all the same size, therefore, they need no screening.

4.2.2 Drying

In the manufacture of cellulosic fiberboard, wet process hardboard, and wet/dry process hardboard, the furnish is not dried because the forming process uses water (see Section 4.2.5). In the manufacture of OSB, PB, MDF, and dry process hardboard, the furnish is dried to a very low moisture content to allow for moisture gained by adding resins and other additives. The furnish is not dried further after blending; however, some evaporation may occur from the heat in the furnish as it comes from the dryer and from air exposure when conveyed from the blender to the forming station. Furnishes are generally no warmer than 100°F when blended to avoid precuring and drying out of the resin (Maloney, 1977).

Rotating drum dryers requiring one to three passes of the furnish are the most common type of dryer used at reconstituted wood plants. The dryers are fired by wood wastes from the plants

(such as bark from OSB plants and fines from PB plants) and occasionally by oil or natural gas. Dryer inlet temperatures may be as high as 1,600 °F with a wet furnish. However, dry planer shavings require that dryer inlet temperatures be no higher than 500 °F because the ignition point of dry wood is 446 °F.

4.2.3 Screening and Air-Classifying

In PB manufacture, screening removes the fines (which would absorb too much resin if not removed) from the dryer exhaust and classifies particles by size for face and core layer (Haygreen and Bowyer, 1989). The PB industry commonly uses inclined or horizontal vibrating screens or gyratory screens (Moslemi, 1974).

Air classifiers, which separate particles by particle surface area and weight, may be used alone or in conjunction with screening equipment. Air classifiers perform best if the feed is limited to particles with uniform widths and lengths. The classifier can then efficiently separate particles of different thicknesses due to the weight difference among particles of approximately equal surface area (Maloney, 1977). Undesired material is sent to a fuel preparation system for the dryer burner. The screened particles are stored in dry bins until they are conveyed to the blender (Vaught, 1989).

4.2.4 Blending

4.2.4.1 Particleboard and Oriented Strandboard

After drying, the furnish is blended with a synthetic resin, wax, and other additives added via spray nozzles, simple tubes, or atomizers. Waxes are added to the furnish to retard the absorption of water into the board. The wax, a mixture of petroleum hydrocarbons, is typically added to the furnish as an emulsion (wax emulsions are dispersions of very small wax particles in water). The dispersion is stabilized with various chemicals known as emulsifiers. The amount of wax added to the furnish ranges from 0.25 up to 1 percent or more of the board weight. Resin may be added to the furnish as received (usually an aqueous solution); mixed with water, wax emulsion, catalyst, or other additives; or added as a spray-dried or finely divided powder (Maloney, 1977). The amount of resin added to the furnish varies anywhere from 2 to 14 percent, depending on the specific end use of the product.

Particles are blended in short retention time blenders in which the furnish passes through in seconds. The blenders consist of a small horizontal drum with high-speed, high-shear impellers and tangential glue injection tubes. As the wood furnish enters the drum, the impellers hurl the furnish at high speeds, which effectively combines it with the resin.

Strands are blended using long retention time blenders that are very large (several feet in diameter and many feet in length). The furnish takes several minutes to pass through these blenders. The blenders are large rotating barrels that are tilted on their axes. As the strands are

fed into the drums, they are sprayed with resin. The tumbling action of the strands through the drums serves to blend the strands with the resin.

4.2.4.2 Medium-Density Fiberboard and Dry Process Hardboard

After refining, the fibers are discharged through a blow valve into a blowline. In the blowline, the fibers are sprayed with a resin. The resin can be injected immediately after the blow valve or anywhere along the blowline (Figure 4-3).

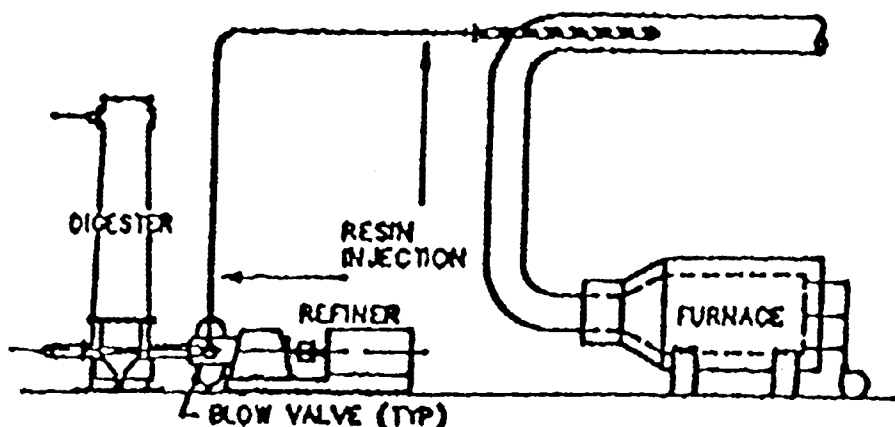


Figure 4-3. Blending system diagram (Frashour, 1990). Reprinted with permission.

4.2.5 Mat Forming

Mat forming is the spreading of the furnish particles into a uniform mat. Mat formation may be a wet, dry, or wet/dry process.

4.2.5.1 Cellulosic Fiberboard, Wet and Wet/Dry Process Hardboard

Cellulosic fiberboard and wet and wet/dry process hardboard are formed by a wet process. In the wet forming process, fibers are mixed with water and adhesive and this water-fiber mixture is then metered onto a wire screen. Water is drained away with the aid of suction applied to the underside of the wire, and the fiber mat along with the supporting wire is moved to a prepress where excess water is squeezed out.

4.2.5.2 Particleboard, Oriented Strandboard, Medium-Density Fiberboard, and Dry Process Hardboard

Particleboard, OSB, MDF, and dry process hardboard are formed by a dry process. The dry forming process uses air to distribute the furnish onto a moving caul (tray), belt, or screen (Figure 4-4). Particleboard mats are often formed of layers of different sized particles, with the larger particles in the core, and the finer particles on the outside of the board (Figure 4-5). In PB and fiberboard manufacture, the particles and fibers are distributed in a random orientation. Oriented strandboard is produced by deliberate mechanical or electrostatic orientation of the strands. In mechanical orientation processes, mats are produced by dropping long slender flakes between parallel plates or disks. In electrostatic orientation, particles align with an electrical field when dropped between charged plates (Haygreen and Bowyer, 1989).

4.2.6 Hot Pressing

All reconstituted wood panels, except for cellulosic fiberboard, are hot pressed to increase their density and to cure the resin. For cellulosic fiberboard, the mat is simply brought to desired thickness using a press roll and then dried in an oven. Wet/dry process hardboard is also dried in an oven before being hot pressed. Most plants use multiopening platen presses (Figure 4-6). Typical multiple-opening presses have 14 to 18 openings (Maloney, 1977).

The last 10 years have seen the introduction of the continuous press (Figure 4-7). Though more popular in Europe, the continuous press is currently being used in two PB and two MDF plants in the United States. The forerunner of the continuous press was the single opening platen press which was very popular worldwide for many years, but gradually has been phased out in the United States.

The hot pressing time needed to compress the mat to final board thickness once the press platens make contact with the mat surfaces is a function of the mat thickness, platen temperature, mat moisture content, and the type of resin and additives used. Phenol-formaldehyde resins need a longer curing time than do UF resins (Maloney, 1977).

4.2.7 Finishing

Primary finishing steps include cooling or hot stacking, grading, trimming/cutting, sanding, and shipping. Cooling is important for UF-resin-cured boards since the resin degrades at high temperatures after curing. Boards bonded using PF resins may be hot-stacked to give additional curing time (Maloney, 1977). Secondary finishing steps include filling, painting, laminating, and edge finishing (Maloney, 1977). However, the vast majority of reconstituted panel manufacturers do not apply secondary finishes to their panels. Panels are primarily finished by end users such as cabinet and furniture manufacturers. Panels are also finished by laminators who sell finished panels to furniture and cabinet manufacturers.

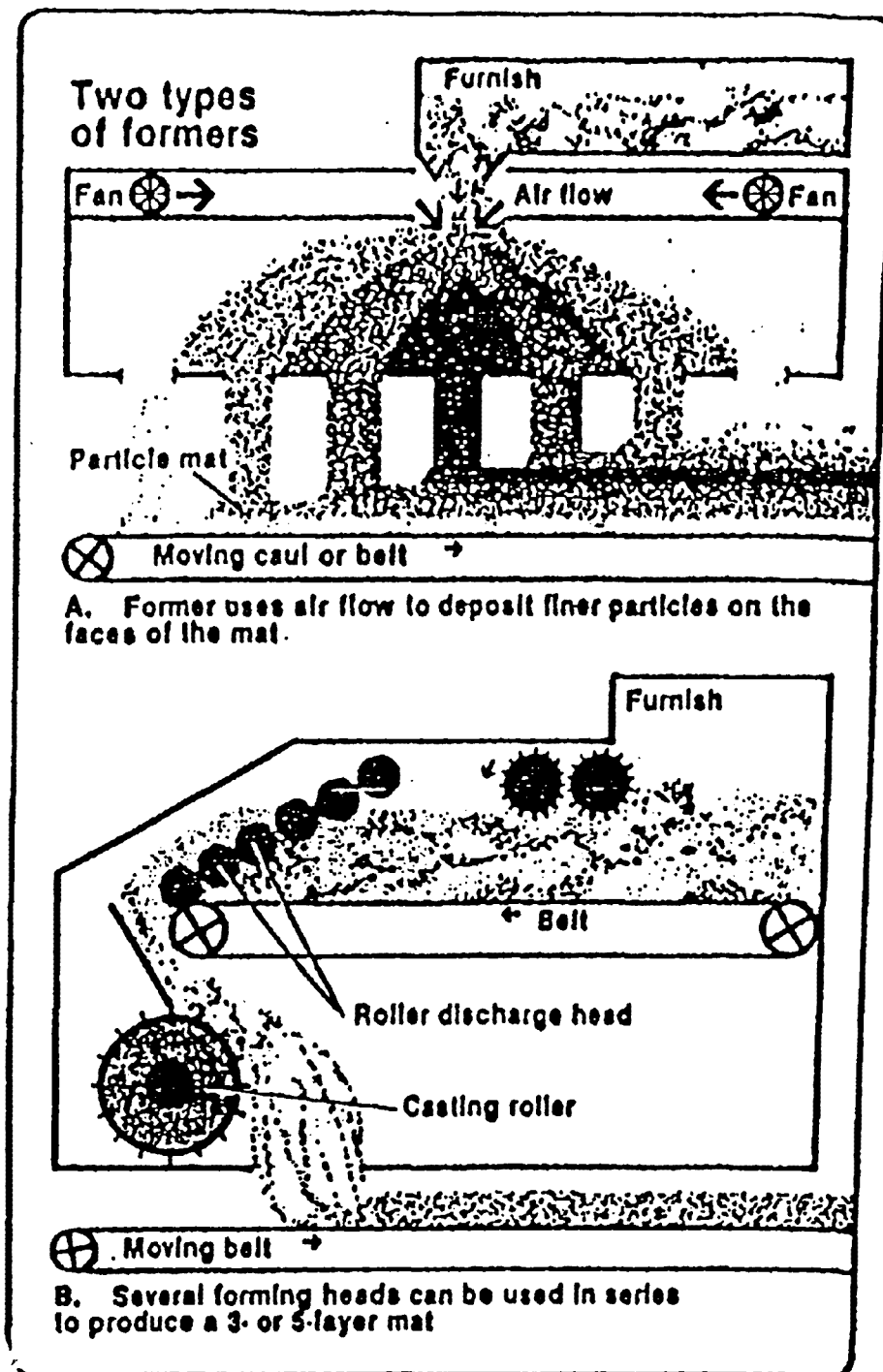
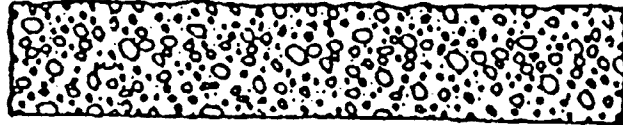
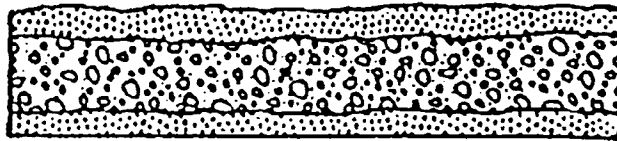


Figure 4-4. Two types of mat forming machines (Haygreen and Bowyer, 1989).
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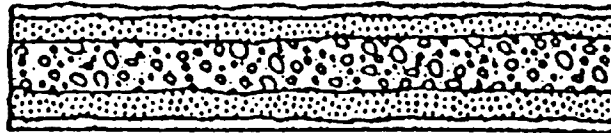
A. SINGLE LAYER



B. 3-LAYER



C. 5-LAYER



D. GRADUATED

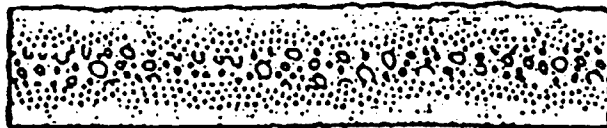


Figure 4-5. Various types of mat construction (Moslemi, 1974). Reprinted with permission.

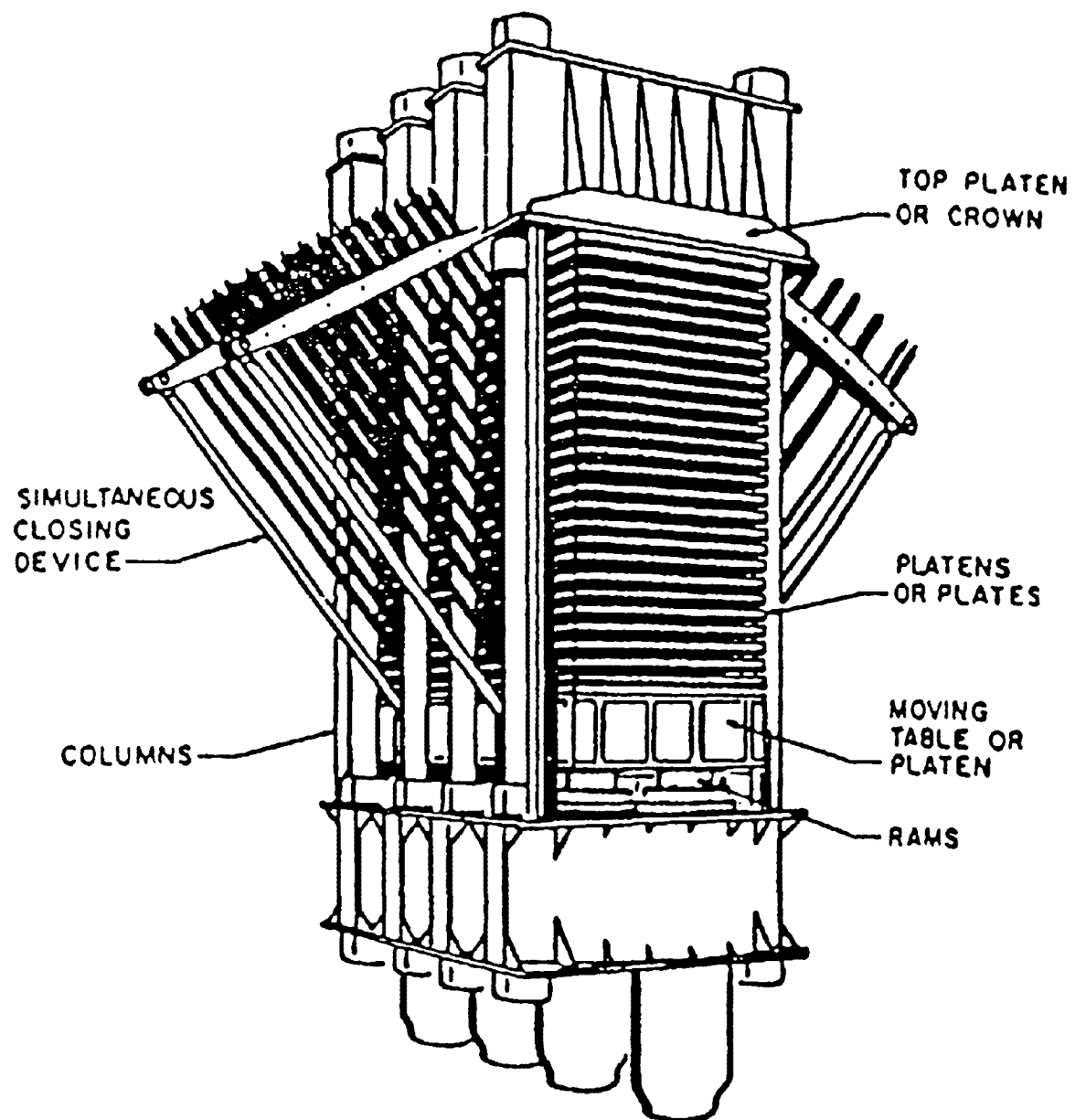


Figure 4-6. Schematic of multiopening board press (Suchsland and Woodson, 1987).

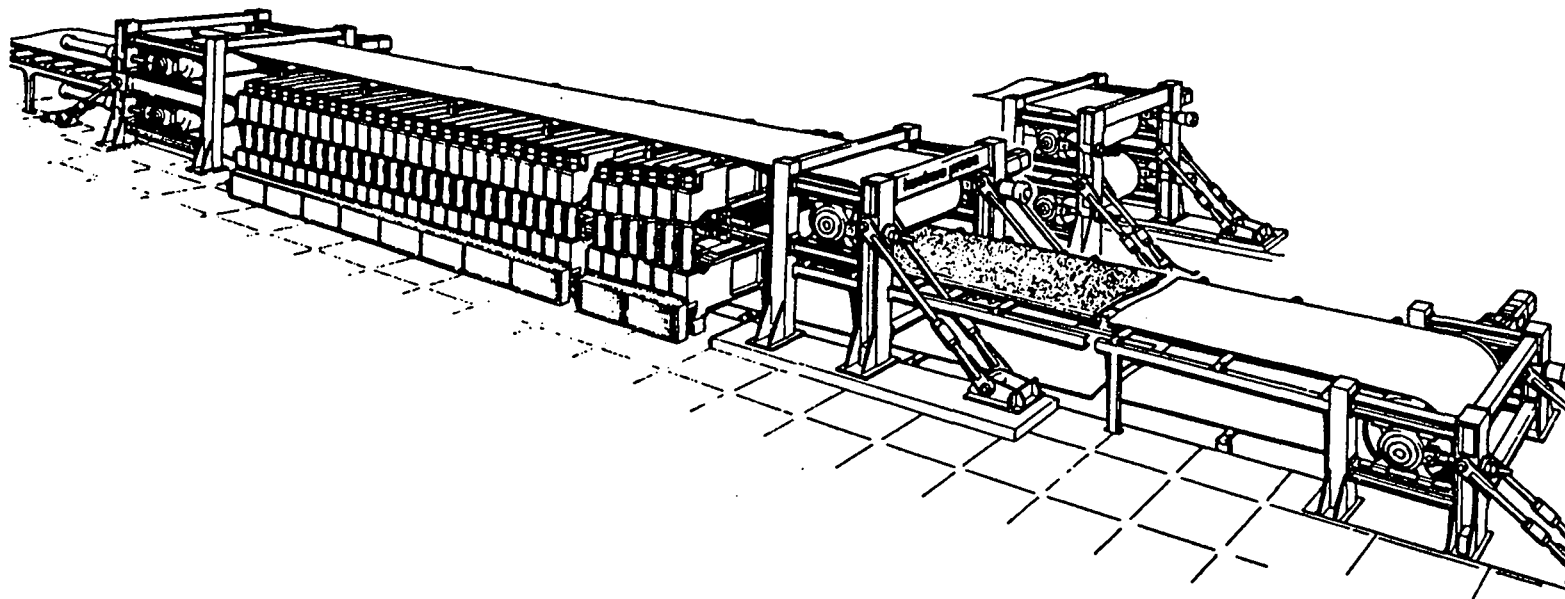


Figure 4-7. Schematic of continuous press (Wolff, 1996). Reprinted with permission.

5.0 EMISSIONS DURING MANUFACTURE OF ENGINEERED WOOD PRODUCTS

Table 5-1 summarizes the 1991 TRI forms filed by plywood plants. Section 313 of Emergency Planning and Community Right-to-Know Act, (EPCRA) (Title III of the Superfund Amendments and Reauthorization Act [SARA] of 1986) requires certain facilities manufacturing, processing, or otherwise using listed toxic chemicals to report their environmental releases of such chemicals annually. Reported air releases were much greater than releases to water or land.

Table 5-1. Reported Releases of SARA Section 313 Chemicals from Plywood Plants for 1991

Compound	Total Releases (10 ³ lb)			Total Transfers (10 ³ lb)	
	Air	Water	Land	POTW	Other Off-site
Acetone	378	0	0	0	5
Ammonium sulfate solution	0	0	0	0	0
Barium compounds	<1	0	4	0	0
Dichloromethane	0	0	0	0	2
Diphenylmethane diisocyanate	10	0	0	0	0
Formaldehyde	86	0	2	<1	0
Glycol ethers	24	0	0	0	0
Methanol	362	0	0	0	<1
Methyl ethyl ketone	79	0	0	0	3
Methyl isobutyl ketone	14	0	0	0	16
Phenol	34	0	4	<1	0
Sulfuric acid	<1	0	0	0	0
Toluene	101	0	0	0	5
Xylenes	76	0	0	0	7

Source: NCASI, 1993.

SARA = Superfund Amendments and Reauthorization Act

Table 5-2 is a summary of 1991 toxics release inventory (TRI) forms filed by reconstituted wood panel plants. Air releases were much greater than releases to water or land. Formaldehyde releases to the air exceeded the releases of all other compounds combined. Since these compounds are emitted during product manufacturing and may be a product or byproduct of the manufacturing process, they can be emitted in the indoor environment.

Table 5-2. Reported Releases of SARA Section 313 Chemicals from Reconstituted Wood Panel Plants for 1991

Compound	Total Releases (10 ³ lb)			Total Transfers (10 ³ lb)	
	Air	Water	Land	POTW	Other Off-Site
Acetone	284	0	0	0	3
Ammonia	78	99	50	63	<1
Ammonium nitrate solution	<1	0	0	0	0
Ammonium sulfate solution	0	<1	1	0	5
Asbestos	0	0	17	0	0
Barium compounds	<1	0	3	0	0
Chlorine	0	<1	0	0	0
Diphenylmethane diisocyanate	4	0	<1	0	0
Ethyl benzene	57	0	0	0	15
Ethyl glycol	27	0	0	0	0
Formaldehyde	3506	<1	51	<1	4
Glycol ethers	40	0	0	0	11
Lead	0	0	<1	0	0
Manganese compounds	0	0	0	48	0
Methanol	622	0	0	0	0
Methyl ethyl ketone	369	0	0	0	39
Methyl isobutyl ketone	117	0	0	0	28
n-Butyl alcohol	110	0	0	0	2
Nitric acid	<1	0	0	0	0
Phenol	184	<1	2	0	0
Polychlorinated biphenyls	0	0	0	0	22
Styrene	0	0	<1	0	2
Sulfuric acid	29	0	0	0	0
Tetrachloroethylene	<1	0	0	0	0
Toluene	799	0	0	0	22
1,1,1-Trichloroethane	0	0	0	0	2
1,2,4-Trimethylbenzene	13	0	0	0	1
Xylenes	431	0	0	0	76
Zinc compounds	0	0	<1	0	0

Source: NCASI, 1993.

SARA – Superfund Amendments and Reauthorization Act.

6.0 SOURCE MANAGEMENT/POLLUTION REDUCTION: APPROACHES AND ISSUES

Some general management techniques for providing good indoor air quality include source management, pollution prevention, source removal/substitution, source modification, increased local ventilation, air cleaning, and general ventilation. Traditional approaches for managing indoor air pollution have relied on the use of ventilation system operating and design changes. These approaches can result in improved IAQ. However, they can also result in substantial increases in energy consumption (for increased ventilation) and transfer of the pollutants to another medium and are inconsistent with the environmental protection hierarchy that was established by the Pollution Prevention Act of 1990.

Pollutants are managed most effectively at their source. The major approaches are chemical substitution, process changes, and product redesign. Strategies vary depending on whether emissions are the result of offgassing from construction or finished materials (e.g., organics in wood products) or product operation or use. When offgassing is the major emissions source, substituting low-emitting materials may be an alternative. When product use or operation is the major source of emissions, knowledge of the relevant process is essential in developing emissions controls or redesigning the product to minimize emissions. In either case, chemical substitution may be warranted if a product or equipment is found to emit chemicals that have been shown to cause serious human health or environmental effects.

6.1 Pollution Prevention

6.1.1 Alternatives to Wood Feedstock

As discussed in Section 3.1.1.1, harvesting restrictions from publicly owned lands have curtailed production of plywood and lumber, particularly in the West. Production of PB and MDF has also been affected by the harvesting restrictions. Over 80 percent of the wood used to manufacture PB/MDF are residuals from lumber or plywood manufacturing such as chips and shavings (McCredie, 1993). Curtailment of the production of plywood and lumber affects the supply of chips and shavings available for the production of PB/MDF. Western board manufacturers have been especially hard hit by the drop in timber supply. Oregon alone has 11 PB/MDF plants that account for more than 25 percent of the U.S. production of these products. The shutdown of plywood and lumber mills has put a premium on the remaining supply of wood residuals (McCredie, 1993). PB/MDF manufacturers that were historically able to satisfy their wood supply requirements within a 100-mile radius of the plant now routinely travel 200 to 300 miles (McCredie, 1993). This results in increased competition for available supplies and increased transportation costs (McCredie, 1993). While no Oregon PB/MDF mills have been permanently shutdown for lack of wood, some production curtailments have occurred (McCredie, 1993).

One potential alternative fiber source for engineered panels is agricultural fibers. Large volumes of agricultural fiber are generated each year in the United States. Sources of this fiber include bagasse, cereal straw, corn stalks and cobs, cotton stalks, kenaf, rice husks, rice straw, and sunflower hulls and stalks (Youngquist et al., 1993). The volume of agricultural fiber generated in the United States is so great that if 75 reconstituted wood panel plants were to switch entirely to agricultural fiber, and, on average, each plant required 135 million tons of fiber annually, more than 30 times as much agricultural fiber would be available as would be consumed (Youngquist et al., 1993). Recently, a plant was built in North Dakota which manufactures particleboard from wheat straw and MDI resins (Galbraith, 1995).

Technically, agricultural fiber may be substituted for wood fiber in the manufacture of engineered products. Whether this is pollution prevention, however, requires a comparison of indoor air emissions and manufacturing emissions from composite agricultural products and engineered wood products. Unfortunately, emissions data from composite agricultural products were not found in the literature to make such a comparison. Consequently, substitution of agricultural fiber for wood fiber is presented in this report only as a “potential” pollution prevention option.

6.1.2 Alternative Resins

Several resin and additive approaches are used by engineered wood manufacturers to reduce formaldehyde board emissions from UF bonded products such as PB and MDF (manufacturers are concerned primarily with formaldehyde because of the IIUD standard). Included are low molar ratio UF resins, the use of formaldehyde scavengers with UF resins, melamine-fortified UF resins, UF resins, and MDI resins. While these alternative resins and additives result in products with significantly lower formaldehyde emissions, only low molar ratio UF resins and formaldehyde scavengers have made a significant penetration in the PB and MDF industry.

6.1.2.1 Low Molar Ratio Urea-Formaldehyde Resins

The formaldehyde-to-urea (F:U) molar ratio is the ratio of the number of moles of formaldehyde to number of moles of urea in UF resin adhesives. For example, a F:U molar ratio of 1.15 has 1.15 moles of formaldehyde for each mole of urea. A wide range of molar ratios is used in UF-bonded products: for PB, when a single resin is used throughout the board, the F:U molar ratio can fall anywhere within the range set by the face/core systems (see Figure 6-1); MDF products use resins with F:U molar ratios higher than PB resins; hardwood plywood products use the highest F:U molar ratios. The nature of the product and process dictates the F:U molar ratio of resin used. The molar ratio directly impacts the ultimate strength the resin will produce in the board, i.e., certain products require higher molar ratio resins to attain an adequate level of bond strength (Rammon, 1990).

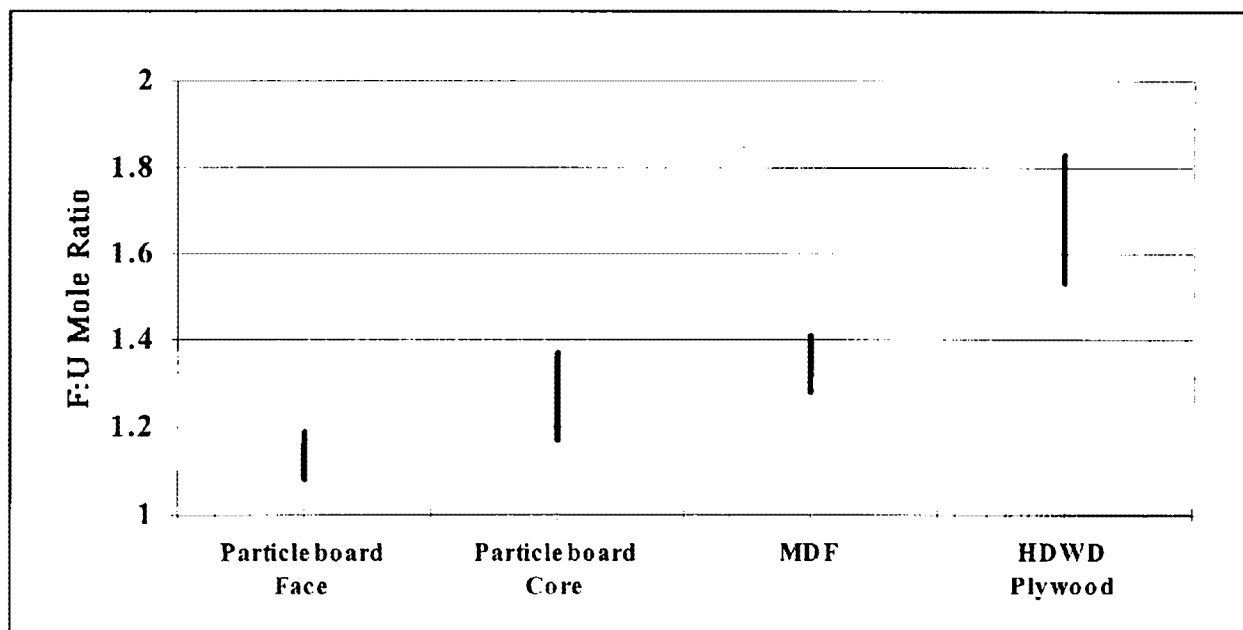


Figure 6.1. Urea-formaldehyde resin mole ratios (Rammon 1990).
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The F:U molar ratio relates to formaldehyde board emissions (Gollob, 1990). The higher the mole ratio, the higher are formaldehyde board emissions and vice versa (Figure 6-2) (Gollob, 1990). However, there are limits to the amount of formaldehyde emissions reduction that can be achieved through lowering the resin molar ratio (Gollob, 1990). As the F:U molar ratio is lowered to somewhere around F:U = 1.00 to F:U = 1.10 (the range is different for different mills), the board properties tend to drop off significantly (Figure 6-3) (Gollob, 1990). Productivity and operating efficiency also drop off significantly (Gollob, 1990).

6.1.2.2 Use of Formaldehyde Scavengers with UF Resins

Another method for reducing formaldehyde board emissions is to use a formaldehyde scavenger with a standard F:U molar ratio resin. Formaldehyde scavengers fall into two distinct categories; scavengers that are incorporated prior to pressing the panel and scavengers that are incorporated after pressing. The basic premise behind the two application methods is essentially the same; both allow the use of a high mole ratio UF resin with all its intended benefits while achieving acceptable emissions by scavenging the excess formaldehyde.

Prepressing Scavengers. Most plants incorporate scavengers prior to pressing the panel. The most prevalent type of prepressing scavenger is chemical urea. Urea is most commonly applied as a 40 percent solution, although some plants use dry powdered urea. Application rates are

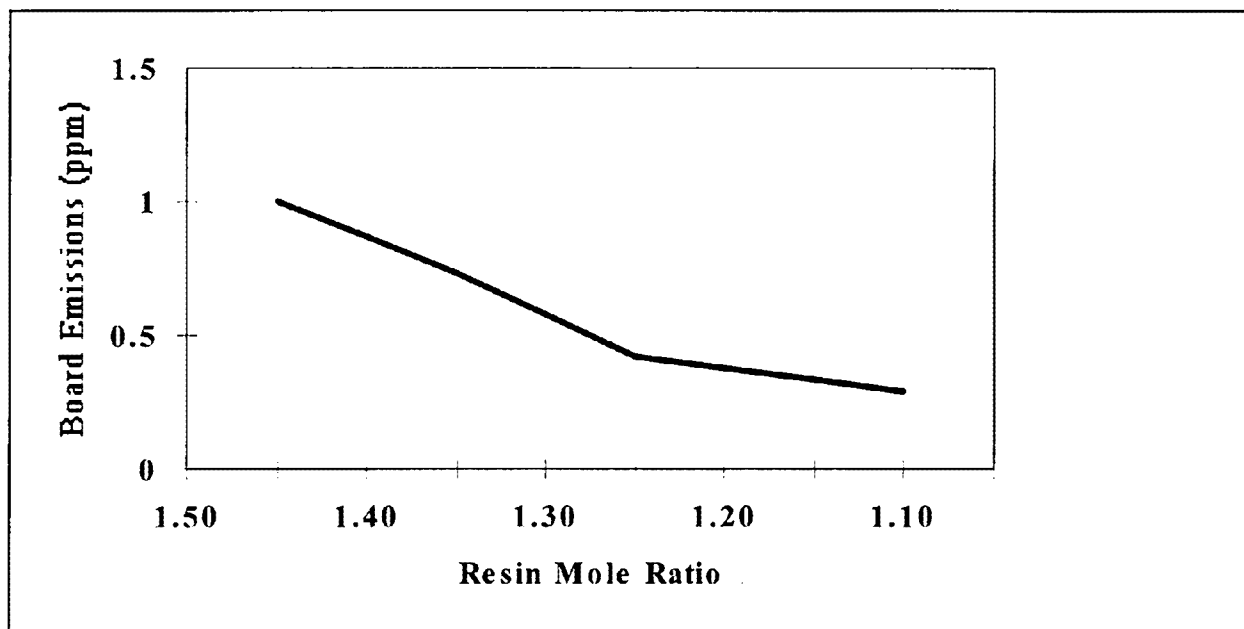


Figure 6-2. Formaldehyde emissions versus F:U mole ratio (Outman, 1991).
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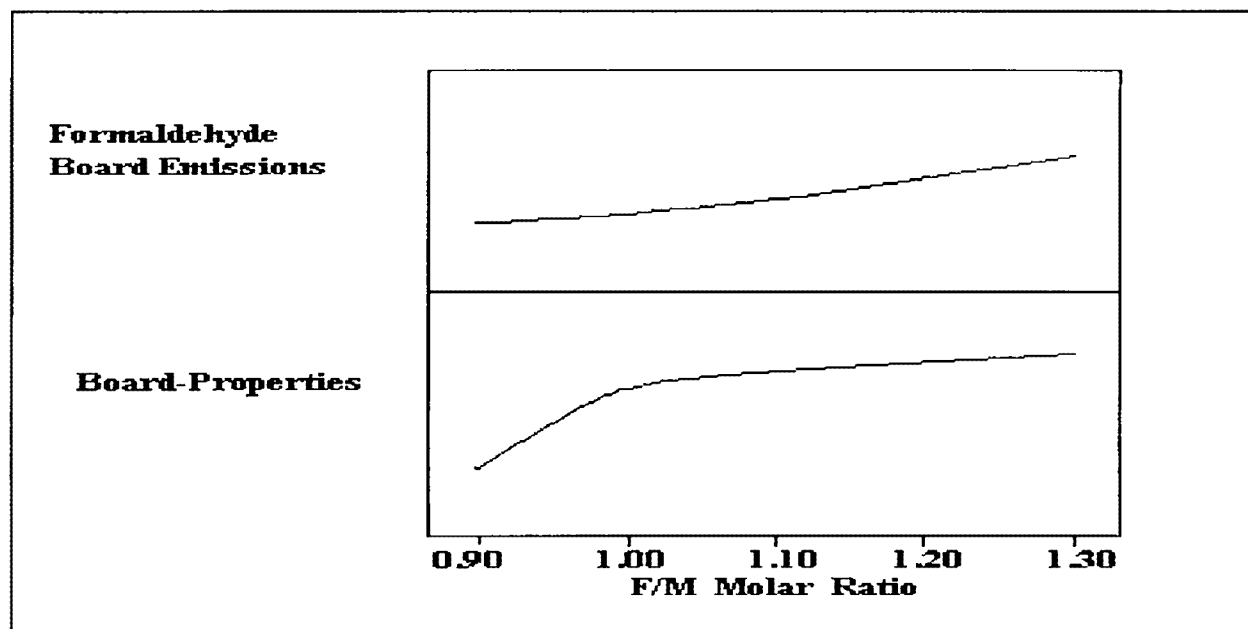
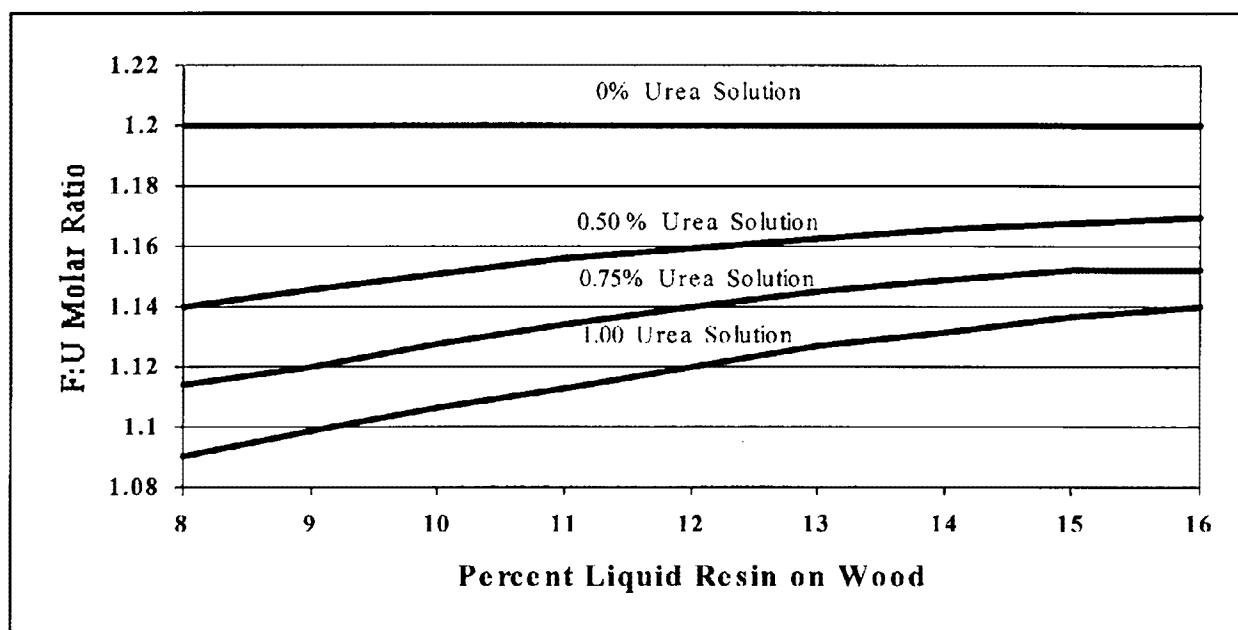


Figure 6-3. Emissions and properties (Gollob, 1990). Reprinted with permission.

generally 0.25 to 1.0 percent urea based on dry wood weight. These levels usually result in formaldehyde reductions of 15 to 50 percent depending on many plant characteristics (Graves, 1990). Figure 6-4 illustrates the estimated F:U molar ratio for urea solutions for the percent liquid resin on wood. The data assume a 40 percent urea solution for the scavenger with calculations set up for F:U = 1.20 molar ratio. However, an equivalent chart can be constructed for any molar ratio. For example, if there were 9 percent liquid resin on wood without a scavenger solution, then the molar ratio would be F:U = 1.20 (Gollob, 1990). As the percent urea solution increases, and is considered part of the resin's F:U molar ratio, the net effect is a decrease in the F:U molar ratio.



**Figure 6-4. Estimated F:U molar ratios with scavenger solution (Gollob, 1990).
Reprinted with permission.**

Another type of prepressing scavenger is a scavenging wax emulsion where the scavenging chemicals are added to the normal wax emulsion. (Wax emulsions are used in engineered boards to retard the absorption of water [see Section 4.2.4.1].) This approach eliminates the need for a separate metering and storage system for the scavenger but does not provide flexibility in scavenger level for different products or conditions (Graves, 1990).

A relatively new prepressing scavenger method is combination blending. Combination blending is the process whereby two liquid UF resins are used in combination to reduce formaldehyde emissions without a loss in board properties or in production efficiency (McAlpine, 1990). The two resins consist of a standard UF resin and an ultra-low F:U mole ratio scavenger resin. Typically, the scavenger resin is combined with the standard resin just before application to the

wood by way of an in-line mixer, although good results have also been achieved using separate application of the two components. Long-term contact of the two components results in a mixture that behaves just like a low mole ratio resin (Graves, 1993).

In one study that evaluated the effectiveness of combination blending, formaldehyde emissions from the panel were significantly reduced without any detrimental effect on board properties (McAlpine, 1990). For the highest level of scavenger resin blended, the study measured a 48 percent reduction in formaldehyde board emissions from desiccator tests (Figure 6-5), and a 63 percent reduction in formaldehyde board emissions from large-scale test chambers (Figure 6-6) (McAlpine, 1990).

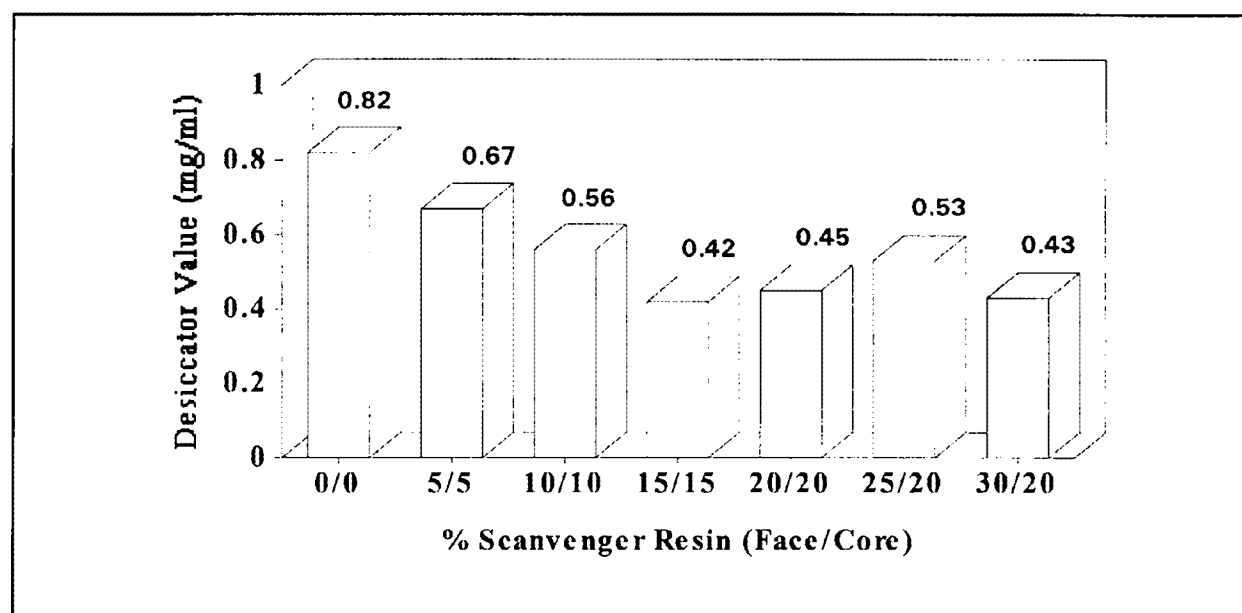


Figure 6-5. Combination blending formaldehyde emissions, desiccator results (McAlpine, 1990). Reprinted with permission.

Postpressing Scavengers. Postpressing treatments are much less common than prepressing treatments but can be very effective (Graves, 1990). The most well known of these is gassing the panels with anhydrous ammonia. Other techniques that have been tried include the application of liquid ammonia or ammonia salt solutions to the board surface prior to stacking. All three methods utilize the reactivity of ammonia toward formaldehyde forming a relatively stable compound (Graves, 1990).

6.1.2.3 Melamine-Fortified Urea-Formaldehyde Resins

Melamine-fortified UF resins have been relatively popular in Europe for many years but have not been widely accepted in North America (Graves, 1993). The appeal of this approach is improved

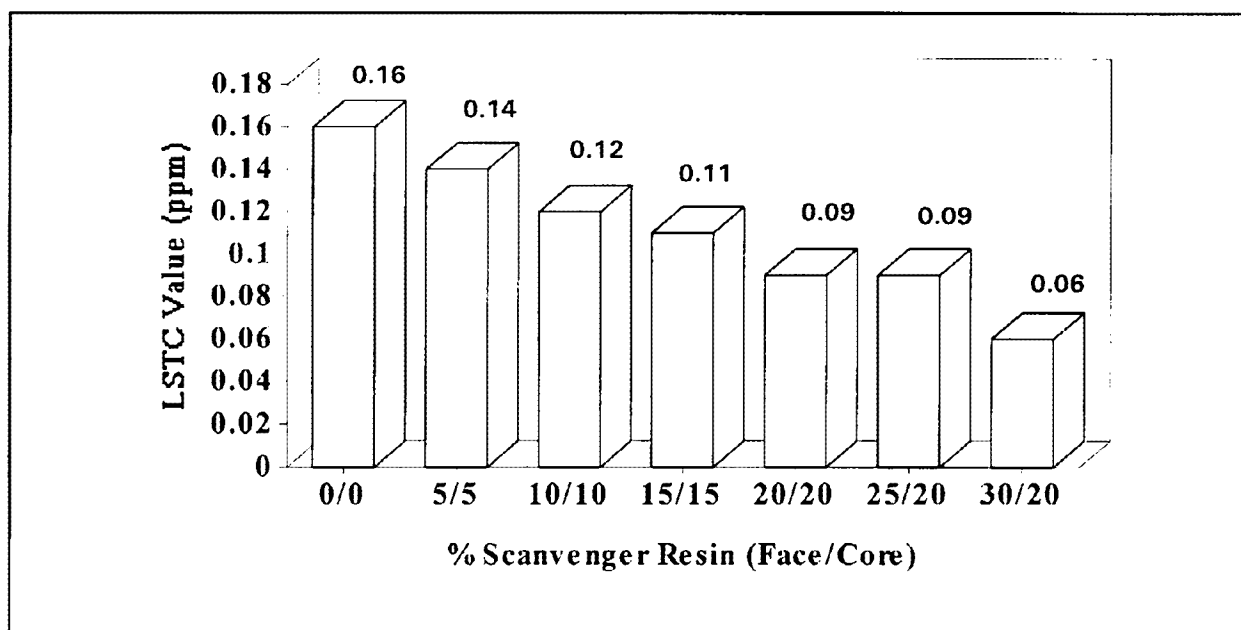


Figure 6-6. Combination blending formaldehyde emissions, large scale test chamber results (McAlpine, 1990). Reprinted with permission.

resistance to hydrolysis contributed by the melamine. Although the amount of melamine used is quite small, generally less than 10 percent based on resin solids, the impact on cost of the resin is significant due to the high cost of melamine. Prices published in the *Chemical Marketing Reporter* (April 2, 1990) list urea at \$0.10 a solid pound and melamine at \$0.40 a solid pound (Gollob, 1990). Thus, urea resins can be fortified with melamine to get a more stable resin, but there is a big increase in the raw materials cost (Gollob, 1990). Successful production trials using melamine-fortified UF resins were carried out at a particular plant in the United States in 1983 and yielded a 40 percent reduction in formaldehyde board emissions with no adverse effects on production or board quality (Graves, 1993). Although proven effective, little acceptance of this approach was forthcoming due to the higher cost of the resin. There have been a few instances where a melamine-fortified resin was used to overcome hot stack degradation problems caused by inadequate board cooling (Graves, 1993). Recently, there has been a resurgence of interest in these resins, particularly to produce panels that will meet the European E1 formaldehyde emissions requirements (Graves, 1993). Production trials have been largely successful, but production volume remains small (Graves, 1993).

6.1.2.4 Phenol-Formaldehyde Resins

Formaldehyde emissions from panels made with phenolic resins are minimal (Graves 1993). Phenol formaldehyde-bonded boards that have been tested, primarily OSB, have had formaldehyde levels that were at, or only slightly above, background levels (Graves, 1993).

Traditionally the two drawbacks that have prevented wide use of PF resins in the manufacture of PB have been resin cost and cure speed. Resin costs would increase about two to three times if phenolic resin were used to replace UF resin, and press cycles would have to be extended 50 to 75 percent (Graves, 1993).

There is one PB producer using phenolic resin on a regular basis (Graves, 1993). In addition to low-formaldehyde board emissions, the board is much stiffer and machines more smoothly than UF-bonded PB (Graves, 1993). Cost and productivity issues could be mitigated by using PF resin only in the surface layer with a conventional UF resin in the core (Graves, 1993). Even so, there is insufficient phenol supply to sustain a large-scale switch to PF resins by the PB industry (Graves, 1993).

6.1.2.5 Methylenediphenyl Diisocyanate

Methylenediphenyl diisocyanate has seen limited use in the PB and MDF industry. It has demonstrated low formaldehyde emissions levels and fast cure speed but has yet to be viewed as an economic alternative to UF resins. In addition, there are concerns about workplace exposures and press platen sticking. Methylenediphenyl diisocyanate has been used in the core layer of PB with a PF resin in the face layer (as commonly practiced in the OSB industry) with some success (Graves, 1993). In addition, it is being used to produce a specialty “no formaldehyde added MDF” to satisfy a niche market (Graves, 1993).

6.2 Novel Adhesives

The three major adhesives used in the wood panel industry (UF, PF, and MDI) are all synthesized from petroleum-derived chemicals. The wood panel industry consumes about 25 percent of the total U.S. adhesives production (Koch et al., 1987). Over the past decade, the price of the raw materials used in these adhesives has grown rapidly. The price of phenol, for example, has more than doubled since 1985 (\$0.45 per solid pound in 1990 compared to \$0.19 per solid pound in 1985). The price of methanol (the basic raw material used to produce formaldehyde) increased from \$0.68 per gal in June of 1994, to \$1.30 per gal in October 1994 (Wellons, 1994). These rapid price increases are a result of increased competition for these raw materials.

The major competition for phenol has come from demand for bisphenol A and caprolactam. Bisphenol A is the feed stock component for polycarbonates that is used to produce automotive plastics, compact discs, and computer discs. Caprolactam is a basic raw material for the production of Nylon 6 that is used in the fast growing stain resistant carpet market. Phenol demands for both bisphenol A and caprolactam are expected to exceed PF resin demand by 1995 (White, 1990). In addition to causing higher prices for PF adhesives, the demand for phenol is reaching world capacity. In 1988, the consumption of phenol equaled 96 percent of the world capacity (White, 1990).

The increase in demand for methanol has been fueled both by general economic improvement in the United States and abroad, and most important, by the growth of methyl tertiary butyl ether (MTBE) as an oxygenate and octane booster in gasoline (Wellons, 1994).^{††} The MTBE market is forecasted to grow from the 1993 level of 4.4 million metric tons to over 8 million metric tons in 1997 (Wellons, 1994). Other major methanol markets, formaldehyde and acetic acid, are forecasted to grow equally to or above the rate of the gross national product (Wellons, 1994).

The significant price increases and potential scarcity of raw material supplies for UF, PF, and MDI adhesives have created interest in renewable raw material sources. Research and development funds are being expended by chemical raw material suppliers, forest products companies, and wood adhesive/binder suppliers to search for renewable raw material sources to replace entirely, or least partially, petroleum-derived chemicals in the manufacture of wood adhesives. Some of the current research is presented below. Naturally derived adhesives are included in this report as pollution prevention because of their potential to use renewable resources, which in many cases are byproducts of other processes. An effort was made to collect information on availability, cost, properties, composition, environmental effects, and stage of product development for each product. Any information found on these topics is included with each adhesive. However, for most of the adhesives, the above information was not found.

6.2.1 FAREZ Resin

FAREZ resin is manufactured from furfuryl alcohol, a derivative of corn. The resin is being evaluated at the University of New Brunswick as an alternative low-VOC binder to substitute for PF resins used for fiberglass insulation products and wood products (Rude, 1994).

6.2.1.1 Environmental Effects

Unlike PF resins, the FAREZ resin is storage stable at ambient temperatures, without refrigeration. As delivered, the FAREZ resin contains very low amounts of volatile components. Upon curing, especially heat curing, the FAREZ resin liberates 80 to 90 percent less total VOC emissions and 80 to 90 percent less emissions of materials on the hazardous air pollutants (HAPs) list (Rude, 1994). The FAREZ system offers the same relative cure speed as the PF resin systems. Various acidic catalyzation options are available that allow either ambient temperature or heat curing capability.

^{††}Carbon monoxide (CO) is a colorless, odorless gas. It is primarily a byproduct of incomplete fuel combustion in exacerbated at high altitudes. Because these environmental conditions reduce combustion efficiency, they increase pollution from motor vehicle exhaust, especially during "cold starts," which last until the engine warms. The CO nonattainment program begins with the division of nonattainment areas into classifications based on the severity of CO pollution. The 1990 Clean Air Act Amendments (CAAA) set forth two classifications of CO nonattainment areas (moderate and serious). Each classification is defined through a range of designated values. Oxygenated gasoline, fuels blended to contain sufficiently high levels of oxygen, is one of the requirements set by States to remedy all or part of a *serious* CO nonattainment area during winter months.

6.2.1.2 Availability

The FAREZ resin is manufactured by the Quaker Oats Company and is currently in the experimental stage of development. The insulation and wood products industries have shown little interest in the resin because of its high cost; the cost of the resin is twice that of a PF resin. However, cost analyses have been performed for the insulation, which show that using the resin to meet future IIAP standards would be cheaper than purchasing and operating control devices such as scrubbers. The same is likely to hold true for the wood product industry (Rude, 1994).

6.2.2 Methyl Glucoside

Researchers at the University of Illinois have been investigating the use of methyl glucoside (MeG), a corn-derived monosaccharide, in the manufacture of plywood adhesives. Researchers have incorporated MeG into plywood adhesives as both an additive and as a partial replacement for phenol in PF resins used in plywood adhesives.

MeG can be incorporated into plywood adhesives either by adding it to the glue mix used at a mill or cooking it into the PF resins manufactured at regional plants. At the mill, MeG can be added to the glue mix as an additional ingredient or it can replace part of the PF resin in glue mix. (Details about the incorporation of MeG into glue mixes is published in Sellers and Bomball, 1990.) Laboratory studies and large-scale mill trials indicate several positive properties from the incorporation of MeG into glue mixes including lower adhesive cost, better dry-out resistance, and better flow properties of the glue. The improved dry-out resistance allows spread reductions of up to 12 percent, resulting in significant cost savings (Dunn, 1993).

A more direct and easier way to incorporate MeG into plywood adhesives is to cook it into the PF resins at the regional distribution plants. The modified PF resins can then be distributed to individual plywood mills, as opposed to attempting to optimize MeG in every plywood mill's glue mix. Laboratory studies have shown that MeG can replace up to 50 percent of the phenol in a base 1.7 to 2.1 formaldehyde to phenol (F:P) molar ratio resin, resulting in a resin with an F:P molar ratio of up to 4.2; wood failure and tensile strengths comparable or superior to conventional resins were achieved with no increases in free formaldehyde or loss in storage stability (Dunn, 1993).

One pollution prevention benefit of adding MeG to PF resins is that the modified resin can bond high-moisture veneer (veneer with 9 percent moisture was bonded in the above studies). The pollution prevention advantage of using an adhesive that is capable of bonding high moisture wood is the potential to reduce VOC emissions from both dryers and presses. Another pollution prevention benefit of adding MeG to the PF resin is that phenol consumption is reduced, which in turn may reduce phenol emissions at the press (emissions data were not found in the literature to confirm this).

6.2.2.1 Future Availability

MeG is made from corn. As the drought of the summer of 1988 demonstrated, even when yields of corn are almost halved, corn surpluses remain sufficient for all current needs (Dunn, 1993). In normal years, American farmers produce nearly twice what is needed in the United States or can be exported (Dunn, 1993).

The incorporation of MeG into PF resins (the easier and more direct way of incorporating MeG into plywood adhesives) has yet to be scaled-up to resin producers/plywood mills. But if the modified resins can be demonstrated on a plant scale, incorporation of MeG into plywood adhesives will proceed at a much faster pace than at present. The long-term goal after successful commercialization of this technology in the plywood industry is to extend this approach to other structural panels such as OSB. OSB panels use a much higher amount of PF resin adhesive because of the higher surface area of the wood strands being glued compared to plywood. The use of MeG in the OSB industry could lead to greater cost savings and pollution prevention benefits through adhesives reduction (Dunn, 1993).

6.2.3 Lignin Adhesives

Lignin is an aromatic polymer made up from phenylpropane units. Lignin makes up one of the three major components of wood, along with cellulose and hemicellulose. In chemical paper processes, such as kraft pulping, lignin is transformed into a soluble form and removed. In 1980, an estimated 20 million tons of lignin (in the form of spent liquor) were produced from kraft pulping in the United States. Only 35,000 tons (0.18 percent) of this lignin was recovered from the spent liquor and used in manufacture of by-products (Zhao et al., 1994).

6.2.3.1 Adhesive Utilization

Lignin can be used as a feedstock for aromatic-based chemicals. Consequently, the abundance of lignin as a waste product in pulp mills has made it a desirable raw material alternative to nonrenewable petroleum-derived chemicals in the production of wood adhesives. Research into utilizing lignin for adhesive production has been going on for years. A large portion of the research has focused on the substitution of lignins for PF adhesives. While 100 percent lignin substitution has yet to be achieved, there has been industrial success with partial substitution of lignins into PF adhesives. Substitution of 20 to 30 percent of kraft lignin into PF resins is common in plywood applications. Until recently, no more than 20 to 30 percent of lignin could be substituted into PF resins because cure times increased as the amount of lignin increased. Another drawback has been that lignin adhesives have low cross-linking and strength. However, recently, a new approach has been developed that can substitute large amounts of kraft lignin for PF adhesives, while actually increasing the cure speed, as well as board strength (Stephanou and Pizzi, 1993). According to research published by Stephanou and Pizzi (1993), a different, and up to now unknown, chemical reaction mechanism has been developed to give "truly competitive kraft lignin-based wood adhesives of good exterior grade performance." The new approach,

which utilizes isocyanates, has been demonstrated on a laboratory scale; exterior-grade PB panels with excellent strength properties were prepared from adhesives containing 46 to 63 percent kraft lignin resin solids, at press times much faster than those used for traditional synthetic PF resins (Stephanou and Pizzi, 1993). The results of this research “. . . clearly indicate that excellent lignin-based adhesives for exterior grade panel products can be manufactured. These adhesives have none of the drawbacks which up to now have been the main stumbling blocks in the effective industrial utilization of lignin for panel binders, namely low cross-linking and strength, and particularly, far too slow pressing times. The adhesives produced gave panels of excellent strength, good durability and very fast press times” (Stephanou and Pizzi, 1993).

6.2.3.2 Availability

Currently, Westvaco is the only U.S. company that operates a commercial lignin extraction facility. In early 1990, the selling price of kraft lignin was approximately \$0.32 per solid pound to \$0.34 per solid pound, and the selling price of phenol was approximately \$0.45 per solid pound (White, 1990). Although an adhesive manufacturer can purchase kraft lignin at a lower cost than phenol, additional processing is required to make the lignin appropriate for adhesive production; the additional processing results in the cost of lignin being equal to that of phenol (White, 1990). However, if the price of phenol continues to rise and exceed the total manufacturing cost of lignin, and assuming sufficient quantities of extracted commercial lignin could be made available, lignin could compete as a partial raw material coreactant with phenol in PF wood adhesives (White, 1990). For there to be sufficient quantities of extracted lignin, additional lignin extraction facilities must be built. The capital cost of a new commercial lignin extraction facility compared to the capital cost of a new phenol plant is estimated to be almost equal per pound of product produced.

6.2.4 Tannin

Tannin refers to a widely occurring group of substances derived from plants. In their most common usage, these substances are capable of rendering raw hides into leather. Common tannin or tannic acid is found in a variety of nuts, tea, sumac, and bark. It is a complex, dark polyhydroxy PF compound.

As a bark product, tannins are readily available. Large quantities of bark are available at mill sites where bark is a waste product of sawmilling and other panel making processes. On average, bark contains 15 to 30 percent polyphenols, 20 to 30 percent lignin, 30 to 45 percent carbohydrates and 1 to 3 percent fats and waxes (Koch et al., 1987). These values are dependent upon wood species, location, age, and exposure.

6.2.4.1 Adhesive Utilization

The use of tannin adhesives for the manufacture of exterior-grade weatherproof PB has gained increased industrial and technical acceptance during the past 20 years (Pizzi, 1983, 1989). Until

recently, all industrial formulations have been based on tannins, such as wattle (mimosa extract of commerce) and quebracho (Pizzi 1983, 1989). In countries where these tannins are produced, wattle and quebracho tannins have been progressively displacing synthetic PF adhesives for manufacturing exterior PB; this progression is attributed to their lower cost and excellent performance (Pizzi 1983, 1989). However, the total worldwide production of these two tannins is only 150,000 tons per year. This is coupled with the fact that the tannin producers do not make more than 20 to 30 percent of their total production available for adhesives application (the rest being reserved for their traditional market, leather). For these reasons, these materials, although industrially and commercially very successful, have had little opportunity to influence the PF adhesives market.

A tannin that can easily be extracted and rendered available in most countries is pine tannin, extracted from the bark of the most diffuse worldwide forestry crop, pine trees (Pizzi et al., 1993). Significant amounts, well into the millions of tons, of this tannin could be rendered available if a successful wood adhesive system based on it could be proven industrially (Pizzi et al., 1993). Recently in Chile, a small industrial producer of native and sulphated pine tannins has developed an adhesive consisting of MDI, tannin, and formaldehyde for exterior-grade PB. Industrial results of extended plant production runs of this adhesive system showed “very encouraging results” (Pizzi et al., 1993).

6.3 Source Management Approaches

6.3.1 Use/Maintenance

Emissions from engineered wood products are due to the emissions of unreacted formaldehyde, hydrolysis of the formaldehyde-based resins, the wood itself, and materials used in product finishing. The rate of formaldehyde emissions has been shown to be greatly affected by temperature and relative humidity. Higher temperatures can increase the rate of emissions, while increased relative humidity increases the rate of hydrolysis. Therefore, keeping the wood products dry and not exposed to high temperatures should reduce the potential for hydrolysis and emissions.

6.3.2 Use of Laminates or Veneers

Although designed for other purposes such as aesthetics, overlays, coatings, and veneers may serve as barriers to emissions (GEOMET, 1994). These coverings can also protect the resins from drastic changes in relative humidity and temperature, thereby minimizing the potential for hydrolytic attack. However, it should be noted that additional resins may be used as adhesives to attach these covers to the wood products. Both UF and PF resins have been used for this purpose and, as a result, increase the amount of resin present as a potential source. Other adhesives used for attaching laminates and veneers include water-based contact cement, epoxy, and polyvinyl acetate. It is possible that adhesives will contribute to their own emissions; however, published adhesive emissions data were not found in the literature to verify this issue.

6.3.3 Bakeout

Offgassing of organics is a major source of pollutants from engineered wood products. While not pollution prevention, bakeout procedure has been suggested to increase the initial emissions of organics, reducing the overall pool of residuals available for later emissions in the indoor environment. Theoretically, this reduces the rate of emissions that would occur during occupancy. During bakeout, the temperature of a new building is elevated and the ventilation is increased prior to occupancy to accelerate the aging of the building materials and furnishings and to increase the emissions rate of free unreacted organic compounds. (Both the temperature and ventilation rate are elevated and increased, respectively, above normal occupancy conditions.) Some researchers believe that this procedure is effective, but just how effective is unknown because offgassing varies with temperatures, time, and ventilation rates (Grimsrud et al., 1988). In addition, in most buildings you cannot increase both the temperature and ventilation sufficiently to reduce sink effects. (Pollutant sinks represent mechanisms by which pollutants can escape the indoor air environment. This escape can occur through deposition on room surfaces, adsorption with those surfaces, reaction with other compounds present in the air, reactions with surfaces, or dispersion to other rooms or outside. Adsorption initially occurs where gas phase molecules are held to the surfaces by relatively weak forces [i.e., Van der Waals forces and weak chemical bonds]. Because these forces are weak, desorption can occur due to a finite mass capacity of the sink and contact with lower concentration air thereby allowing the molecules to be re-emitted into the indoor air environment.) Finally, this practice may be limited by the potential damage that can occur as a result of subjecting certain types of materials (e.g., wood products) to higher temperatures. For example, bakeout may lead to excessive drying and result in stresses that affect both the appearance and structural integrity of some wood products.

7.0 CONCLUSION

This report summarizes information collected from existing sources and a research planning meeting. The compiled information was used to choose several products for source characterization studies. Once these emission studies are complete, pollution prevention options will be identified and evaluated. Interim papers on preliminary research results will be presented at appropriate conferences or symposiums. A final report featuring the research conducted under this cooperative agreement between EPA and RTI will be issued upon completion of the research in 1996. An evaluation of the health and environmental effects was beyond the scope of work for this project.

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Appendix A

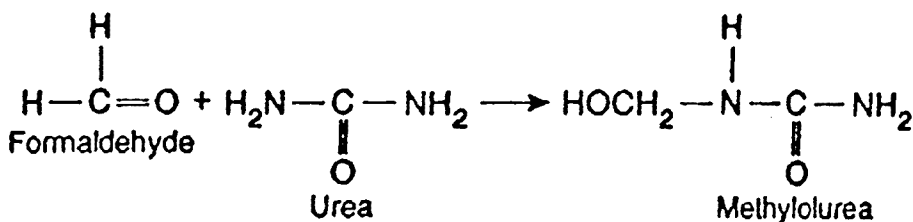
Chemistry of Formaldehyde-Based Resins

This appendix presents a detailed discussion of resins used in the manufacture of composite wood materials. The literature on resins is rather extensive to be reviewed even superficially; therefore, the reader may wish to review a polymer chemistry handbook for more detailed information.

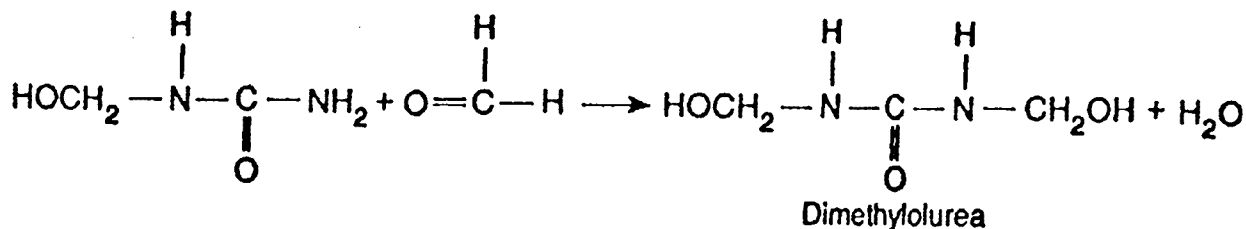
A.1 Urea-Formaldehyde Resins

Urea-formaldehyde resin was patented in 1920 by Hanns John, Magister of Pharmacy of Prague (Meyer et al., 1986). The main difference between early urea-formaldehyde resins, whose mechanisms are depicted below, and modern wood adhesive resins is quality control during manufacturing and molar ratio of the reagents, urea and formaldehyde (Meyer et al., 1986).

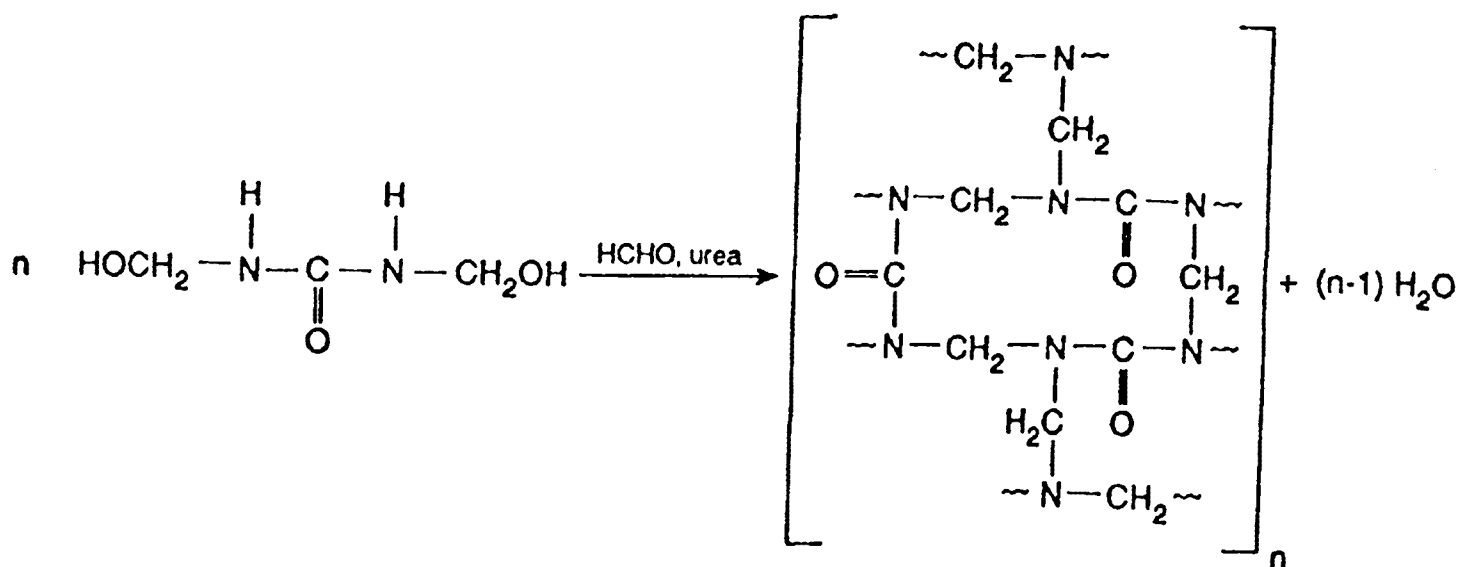
Urea, H_2NCONH_2 , reacts with formaldehyde to form urea-formaldehyde resins. The four hydrogen atoms in a urea molecule are potentially reactive. Proper cross-linkage is important for resin production. Formaldehyde is added, and it reacts with unreacted $-\text{NH}_2$ groups to provide chemical cross-links between polymer chains. When urea and formaldehyde react on an equimolar basis, the following reactions occur to eventually produce the urea-formaldehyde resin:



A monomer is the intermediate product. It polymerizes further to produce a thermoplastic resin and water.



Eventually:



Some additional formaldehyde is needed to react with a few of the unreacted -NH₂ groups and to provide chemical cross-links between polymer chains. This additional formaldehyde is significant to the formation of urea-formaldehyde for several reasons. First, an excess of formaldehyde results in quicker polymerization, which in turn results in lower manufacturing costs. Second, sufficient formaldehyde is necessary to provide adequate polymerization and produce satisfactory properties of the desired final product. Finally, excess formaldehyde results in unreacted formaldehyde in the final product. This excess formaldehyde, also called "free formaldehyde," slowly diffuses from products and may result in increased formaldehyde concentrations in indoor air when these products are used indoors (NRC, 1981).

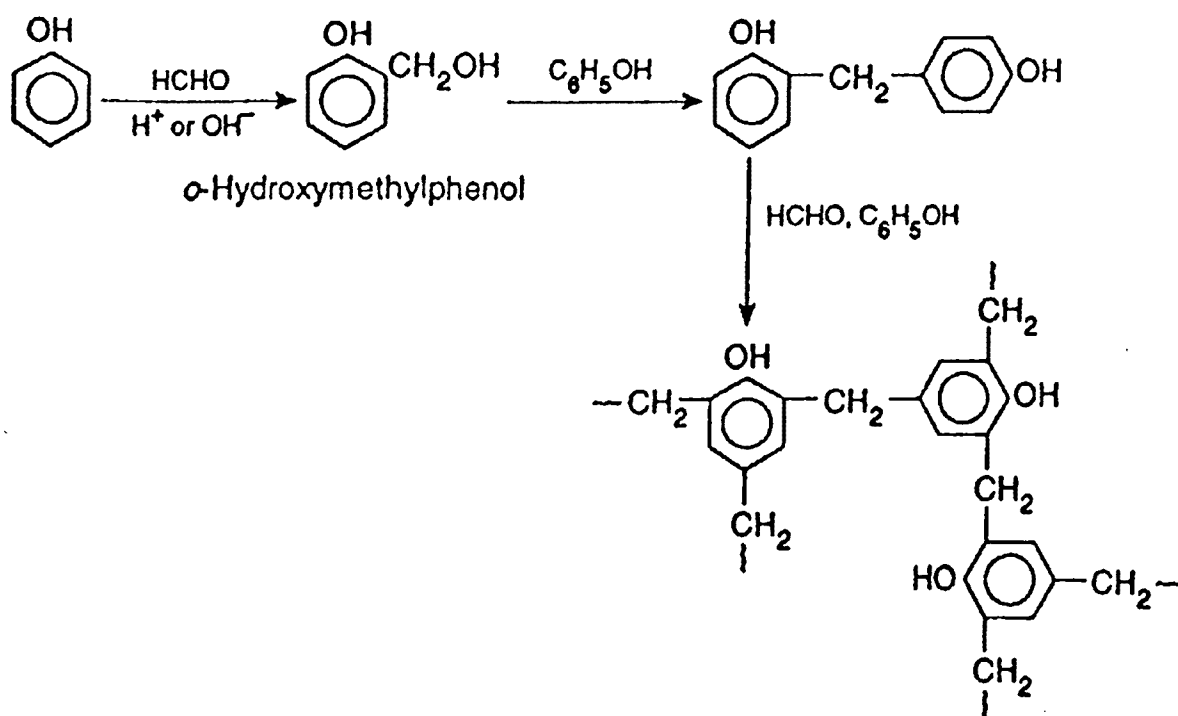
Originally, the formaldehyde-to-urea molar ratio for the urea-formaldehyde resin was 2. This molar ratio corresponded to the number of chemically reactive groups present in the reagents and provided for sufficient formaldehyde polymerization of all primary and most secondary amino groups. In the early 1980s, most urea-formaldehyde resins marketed as wood adhesive resin contained a molar ratio of 1.8 for formaldehyde to urea although proof was available that lowering the overall molar ratio further reduced the potential for postmanufacture formaldehyde release (Meyer et al., 1986).

Nonetheless, progress has been made in formulating low-molar ratio resins and in capturing unreacted methylol groups. Current adhesive resins are manufactured in three or more steps. The first step still involves the addition of urea to a highly concentrated formaldehyde solution, frequently with a formaldehyde-to-urea ratio of 4. This reaction produces a mixture of methylol compounds. Modifications in modern resin production require that urea be added two or three times. These additions bring the overall molar ratio down to a sufficient level

(lower than 1.8) to retain unreacted amino groups. Amino groups behave as scavengers of formaldehyde that was unreacted or released by hydrolysis of unreacted methylol functions (Meyer et al., 1986).

A.2 Phenol-Formaldehyde Resins

Reactions of phenol and formaldehyde produce phenol-formaldehyde resins. Phenol reacts with both formaldehyde and paraformaldehyde in the presence of an alkali or acid medium to produce the phenolic resin. The phenol-formaldehyde reactions fall into two groups: (1) the formation of methylol phenols, called phenol alcohols, and (2) the formation of polynuclear methylene derivatives. The following is an example of the reaction mechanisms involved in the former group to form the phenolic resin:



Stages involved in the formation of the phenol-formaldehyde resin presented above are as follows:

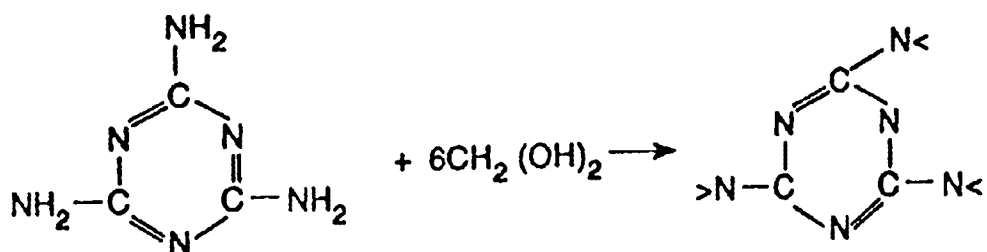
- Phenol and formaldehyde react in an acidic or basic medium to form *o*- or *p*-hydroxymethylphenol.
- Hydroxymethylphenol reacts with another molecule of phenol.
- Then water is lost, and a compound with two rings joined by a $-\text{CH}_2-$ link is formed.

Three positions on each phenol molecule are susceptible to attack, which makes the reaction process difficult to control. Condensations contain many cross-links and produce a high-molecular-weight polymeric product. The general class of such polymers, phenol-formaldehyde resins, is the final product. Bakelite is the name of this dark, brittle, cross-linked polymer. The phenolic resin is one of the oldest synthetic polymers.

Very little free formaldehyde is present in phenolic resins; therefore, emissions are lower than those of urea-formaldehyde resins. The low free formaldehyde content is due to both the low formaldehyde-to-phenol molar ratios in resin synthesis and the tendency of nearly all the formaldehyde to react irreversibly with phenol. The little residual formaldehyde present is reduced further by reactions that occur when the phenolic resin cures. Under curing conditions, unreacted formaldehyde continues to react with phenol to form larger phenol-formaldehyde polymer chains.

A.3 Melamine-Formaldehyde Resins

Melamine, a cyclic trimer of cyanamide, reacts with one to six molecules of formaldehyde, producing mono- to hexa-methylols. These six methylol compounds are often used to prepare melamine resins. Melamine and urea chemistries are similar. Boiling the proper melamine-to-formaldehyde ratio for a short time produces hexa-methylols. The reaction mechanism for melamine and formaldehyde is as follows:



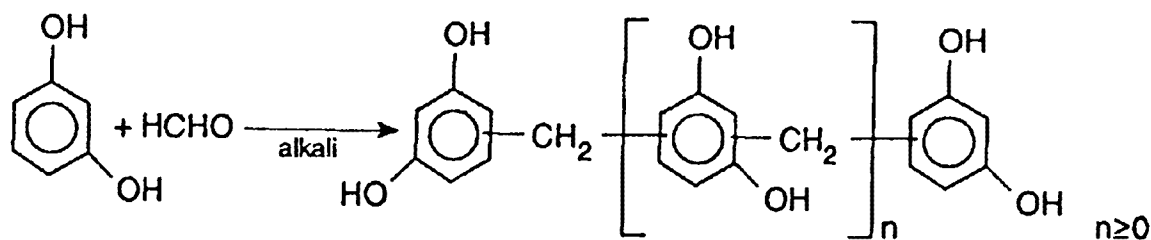
Melamine offers six hydrogen atoms to react with formaldehyde to form melamine resins. Unlike the four potentially reactive hydrogen atoms of urea used to form urea-formaldehyde resins, this reaction yields better cross-linking, and, thus, better water-resistant adhesives are produced.

In addition, blends of melamine-formaldehyde resins with cross-linked novalak phenol-formaldehyde resins are used to produce melamine-formaldehyde phenol-formaldehyde formulations suitable for exterior exposure. (Novalak phenol-formaldehyde resins are linear in structure and require heat to cure plus hardener to improve crosslinking.) The hardwood and laminating industries use urea-formaldehyde/melamine-formaldehyde blends for products that require improved durability over that of UF and light-colored glue line (Sellers et al., 1988).

A.4 Resorcinol-Formaldehyde Resins

Resorcinol-formaldehyde has been in use since 1943 (Pizzi, 1983). Resorcinol-formaldehyde resins are synthetic polymer resins based on the condensation reaction of formaldehyde (derived from methanol) and resorcinol (derived from benzene) (Koch et al., 1987).

The resorcinol-formaldehyde resin is formed by the reaction of resorcinol with deficient amounts of formaldehyde (less than required for complete cure). Additional formaldehyde is added at the time of application where curing to a solid state takes place. The following schematic depicts this reaction:



A.5 Diphenyl-Methane-Isocyanate (Methylenediphenyl Diisocyanate)

The copolymer methylenediphenyl diisocyanate (PMDI), is a member of the family of isocyanates that are generally low-viscosity liquids formed through phosgenation of the reaction products of aniline and formaldehyde. Isocyanates are oil-based products derived from naphtha as shown in Figure A-1. PMDI is known for its bonding strength. Thus, it has

become a prominent adhesive candidate. PMDI has several synonyms, including diphenyl-methane-isocyanate and methylenediphenyl diisocyanates (MDI). The commercial product, known as diphenyl-methane-isocyanate, $\text{C}_{12}\text{H}_{10}\text{N}_2\text{O}_2$, is the reaction product of a urethane bridge:



where **R** is wood cellulose, copolymer, or filler. Not only does PMDI adhere to wood, but it also adheres to metal surfaces of the presses used in composite wood product fabrication. Consequently, when PMDI use is not confined to the core of the fabricated composite wood product, a special release agent is needed to detach the composite wood product from metal surfaces of the press.

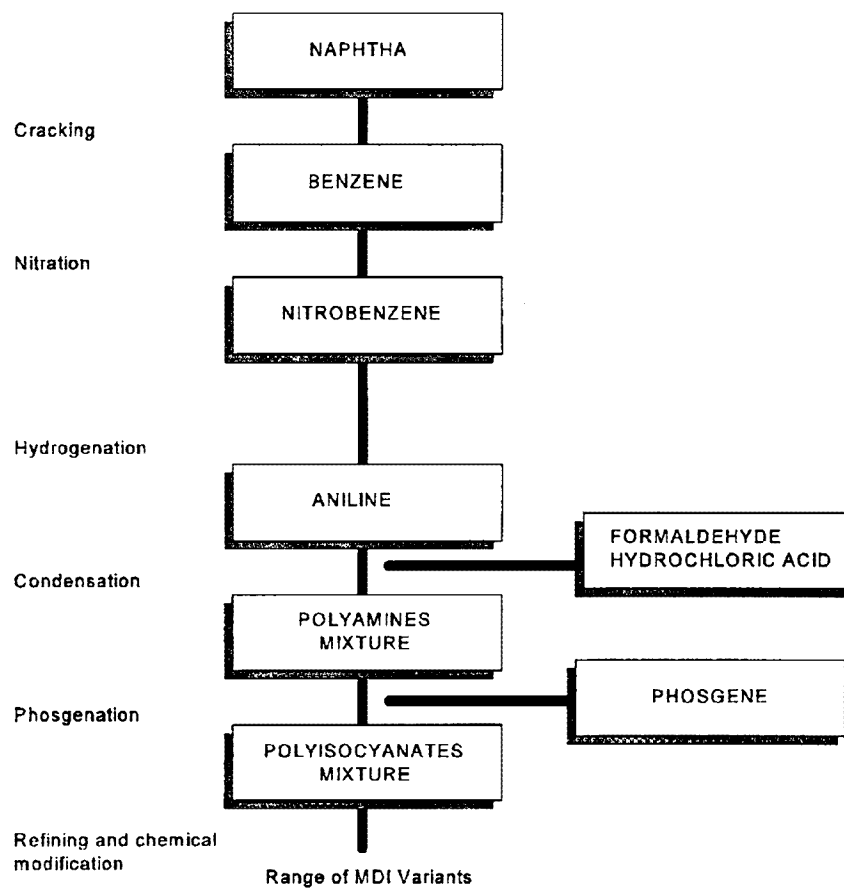


Figure A-1. Manufacturing route to isocyanate (Ball, 1981).

Appendix B

Summary of Indoor Air Emissions Research

Section 2.0 of this report discusses indoor air emissions from finished and unfinished composite wood. Results from several studies of emissions from composite wood products are summarized in this appendix.

B.1 Mølhave Study

In a 1982 Danish study, Mølhave determined organic emissions from 42 building materials. This analysis suggested that building materials may be the primary source of organic compounds in the indoor environment (Mølhave, 1982). In this study, Mølhave identified 52 different chemical compounds from the air around 42 building materials. Surface materials, such as plywood and fiberboard, and materials normally used in interior construction, such as particleboard, account for five products or 12 percent of the materials studied.

Surface materials were delivered directly from production or factory stock. The producers cut them in standard A2-format ($420 \times 594 \text{ mm}^2$) and wrapped them in heavy polyvinylidenechloride foil to prevent contamination. The emissions concentrations were measured in the air around 0.25 m^2 of test materials in a 1-m^3 stainless steel chamber supplied with 0.69 liters fresh air per minute (one air change per 24 hours at 21.1°C [standard deviation = 1.7°C]) and 35 to 40 percent relative humidity. The exhaust from the chamber was analyzed using combined gas chromatography/mass spectrometry (GC/MS) for the qualitative and quantitative analysis. Industrial gas detection tubes were applied for aldehyde, especially formaldehyde, detection.

The results for the five composite wood products that were evaluated as part of this study are presented in Table B-1. All five materials were characterized as building materials used in walls. The first three materials, which are particleboards, were further categorized as materials used inside the construction, and the plywood and fiberboard were categorized as surface materials. Formaldehyde emissions were not examined from the first two particleboard samples listed in the table. Although the remaining three materials in Table B-1 were analyzed for aldehyde emissions, no reaction took place in the industrial gas detection tubes. Consequently, formaldehyde emissions were not detected.

Of the 52 different chemical compounds (representing 10 chemical categories), Mølhave identified 10 chemical compounds as most frequently found in the air around the 42 building materials tested. Those compounds are categorized as aromatic compounds and alkanes and represent a total average concentration of $72.96 \mu\text{g}/\text{m}^3$. Although the author stated the number of compounds detected and identified, he did not specifically identify the chemicals emitted from each tested building material. The identification of chemicals emitted from each material would have been valuable information for this report. Instead, Table B-1 lists the

average concentration of organic vapors emitted by each composite wood material, their specific emissions rates, and the number of compounds detected and identified.

Table B-1. Results of Analysis of Air Around Materials

Type of Material	Organic Concentration (mg/m ³)	Emissions Rates (mg/m ² -h)	Number of Compounds	
			Detected	Identified
Particleboard	1.56	0.120	29	10
Particleboard	1.73	0.130	28	11
Particleboard	3.56	0.140	24	7
Plywood	1.07	0.044	16	0
Wood fiberboard	2.96	0.120	23	7

Excerpted from: Mølhave, 1982.

B.2 Levin Study

Using software developed by the U.S. Environmental Protection Agency (EPA), Hal Levin and Associates, architectural consultants, tabulated model predictions of typical emissions rates from sources in a 400-m² office area (Levin et al., 1989). To construct the model, EPA researchers used the results of chamber, headspace, and test house experiments to construct a model to predict the total volatile organic compound (TVOC) concentrations in indoor air (Sparks et al., 1988). Source strengths and ventilation rates were also used in the model to compute the typical emissions factors and emissions rates for assumed product loadings of various products.

The predicted emissions rates of four composite wood products and their assumed product loadings are shown in Table B-2. The estimates for two sources, the second particleboard sample and the plywood panel, represent predicted formaldehyde (HCHO) emissions only. The estimates for the two remaining samples, the first particleboard and chipboard, depict predictions for TVOC emissions. The first particleboard was 2 years old; the other particleboard and plywood panels were new. Information on the condition of the chipboard was not available. Table B-3 lists organic compounds emitted from composite wood products. The tabulated information was extracted from an appendix table in Levin et al. (1989). Source types are those for which quantitative data on emissions have been obtained from chamber tests or for which qualitative data are available from many sources (Levin et al., 1989). Unfortunately, emissions data were not listed in the original table.

Table B-2. Typical Predicted Emissions Rates for Sources in 400-m² Office Area

Source ^a (Noted Emissions Type)	Emissions Rate (mg/m ² -h)	Assumed Product Loading	Mass Flow Rate
Particleboard (TVOC)	0.20	300	60
Particleboard (HCHO)	2.00	300	600
Plywood paneling (HCHO)	1.00	1000	1000
Chipboard (TVOC)	0.13	300	39

Excerpted from: Levin et al., 1989.

^a The data do not represent all products of the source type listed. Product-to-product variability can be very high.

Table B-3. Sources of Indoor Organic Compounds

Compounds ^a	Substantiated Sources ^b
Formaldehyde	Plywood, particleboard
Ethanol	Fiberboard
Isopropanol	Particleboard
n-Hexane	Chipboard
2-Methylpentane (isohexane)	Chipboard
Benzene	Particleboard
Benzaldehyde	Fiberboard, particleboard
Ethylbenzene	Chipboard
1,2,4-Trimethylbenzene	Chipboard
n-Propylbenzene limonene	Chipboard
Limonene	Chipboard
α -Pinene	Chipboard
Undecane	Chipboard

Excerpted from: Levin et al., 1989.

^a Selected compounds that have been measured in indoor air and that may have come from material sources.

^b Source types for which quantitative data on emissions have been obtained by chamber tests or for which qualitative data are available.

B.3 Saarela Study

In this study (Saarela and Mattinen, 1993), TVOC concentrations as a function of time were measured in a new office building with ventilation operating at high efficiency and with ventilation switched off. The office building ventilation rate was 2.5 air changes per hours (ACH) from Monday morning to Friday evening. Ventilation was switched off on Saturday.

The new two-floor office building was divided into two parts; eastern and western sections were separated by a staircase and sanitary rooms. The two floors consisted of open and closed office spaces, a conference room, and a single, unfurnished space that was not in use at the time measurements were made for this study. The reader is referred to the original document (Saarela and Mattinen, 1993) for a more detailed description of the building.

This study was conducted to establish the types and quantities of airborne chemicals in a new office building and the influence of ventilation on the indoor concentrations of these chemicals. Air samples were taken on both floors of the new office building in the center of the open spaces at a height of 1.5 meters. The organic samples were collected in glass tubes containing 150 mg of Tenax TA absorbent. Chemical compounds were identified with a Jeol SX-102 mass spectrometer. Of the identified compounds, the most abundant were chosen for quantitative followup done with an HP 5890 Series II GC equipped with a flame ionization detector (FID). The total VOC values were calculated from the FID-detector response in toluene equivalents. Aldehydes were measured from one site in the building under both ventilation conditions and were collected in impinger flasks containing dinitrophenylhydrazine (DNPH) dissolved in 2-M HCL and analyzed with high-performance liquid chromatography (HPLC).

The measurements taken for an 8-month period in the ventilated building displayed a random variation of individual organics. Table B-4 lists the most abundant organics selected for quantitative determination and their maximum concentrations with ventilation on. In this study, the maximum concentration of formaldehyde reached 0.122 mg/m³ with no ventilation; however, the formaldehyde concentration was 0.059 mg/m³ at week 8 of the 8-month study with ventilation. In both ventilated and unventilated buildings, aldehydes show an upward trend in the beginning (Saarela and Mattinen, 1993). In the unventilated building, the trend for most of the identified aldehydes was initially rising concentrations, but concentrations began to decline after 4 to 8 weeks. In the ventilated building, the aldehydes show an upward trend on weeks four to eight. The authors concluded that new materials produced high emissions levels and that, with effective ventilation, the resulting concentrations could be reduced to levels that would not cause discomfort or adverse health effects.

B.4 Meyer Study

The author of this study used data from other sources to compile a table of construction materials and consumer products (Meyer, 1983). The range of formaldehyde emissions rates for seven composite wood products, extracted from a list of the 28 construction materials and consumer products, is provided in Table B-5. Recorded emissions rates of these products

Table B-4. Concentration Measurements of Organics in a Ventilated Building^a

Chemical Compound	Maximum Concentration (mg/m ³)
Toluene	0.121
Formaldehyde	0.059
Octane	0.011
Ethylbenzene	0.007
m+p-Xylene	0.013
Styrene	0.008
o-Xylene	0.011
α -Pinene	0.004
1,2,4-Trimethylbenzene	0.002
Decane	0.003
Undecane	0.004
Dodecane	0.002

Excerpted from: Saarela and Mattinen, 1993.

^a Measurements depict the average and maximum concentrations during an 8-month period.

Table B-5. Range of Formaldehyde Emissions Rates for Seven Composite Wood Products

Material	Emissions Rate (mg/m ² -day)	Reference
Plywood		
UF-bonded	1-34	a
Phenolic	0-0.05	b
Hardwood paneling (UF)	1-34	b
Particle board		
Standard (UF)	2-34	b
Low emissions (UF)	0.5-3	b
Phenolic	0-0.001	b
Plywood	0.055	a

Excerpted from: Meyer, 1983.

^a Pickrell et al., 1982.

^b Meyer, 1979; Meyer et al., 1980; see also Spedding and Edmondson, 1980; Lehmann, 1982; and Sundin, 1982.

were based on a few samples and on a small number of measurements. Therefore, they represent a range rather than average emissions rates for the entire class of materials. The literature from which the author obtained the data is also listed.

B.5 Sundin Study

In this study, researchers measured organic emissions including formaldehyde from several commonly used building materials (Sundin et al., 1992). The materials evaluated included planed pine lumber, coated and raw particleboard of different ages, medium-density fiberboard (MDF), hardboard, plywood, and gypsum board. Dried, unresinated sawdust and shavings were also included.

An active sampling method was used to collect samples. A special device was fabricated to extract air samples from the surface of the materials analyzed. This device included a cover consisting of a desiccator lid attached to a pump by a tube containing the adsorbent inline and a glass plate for the bottom. Each sample was enclosed in the device, and air was extracted from the surfaces of the materials and adsorbed on charcoal and Tenax tubes. The adsorbed organic compounds were analyzed using a GC/MS. The emissions of formaldehyde were evaluated separately at the Casco Nobel research laboratory in Sundsvall, Sweden. Independent of the analysis performed at the Casco Nobel Research Laboratory, formaldehyde was also measured with the Interscan Portable Formaldehyde analyzer 1163.

Table B-6 lists TVOC and formaldehyde concentrations emitted from the tested materials. Table B-7 contains the concentration percentages of aldehydes and terpenes from the TVOC concentrations. The authors of this study concluded that:

- The identified VOCs emitted from building materials showed good agreement with the published findings of Nelms et al. (1986).
- The decay process for VOCs emitted from particleboard takes place very rapidly with a half-life of 3 months or less.
- Particleboard coated with melamine film has relatively high VOC emissions immediately after pressing due to the organic emitters present in the film. However, measurements after 1 month showed that VOC concentration levels are similar to other investigated materials.
- Ordinary pine lumber has outstandingly high VOC emissions concentration ($920 \mu\text{g}/\text{m}^3$) among the materials studied. The emissions consists largely of terpenes. The decay process has not been studied.

Table B-6. VOC and Formaldehyde Emissions from Various Engineered Woods

Type of Material	Total VOC		Formaldehyde		
			InterScan ^a		Chamber ^b
	mg/m ² -h	mg/m ³	mg/m ² -h	mg/m ³	mg/m ³
Hardboard, standard 3.2 mm	0.03	0.09	0.03	0.02	0.03
Hardboard, oil-treated 3.2 mm	0.03	0.08	0.03	0.02	0.02
Plywood, UF, 10 mm	0.05	0.15	0.03	0.02	0.05
MDF, UF, 16 mm	0.04	0.11	0.79	0.50	0.97
Lumber, planed, pine 170×25 mm	0.31	0.92	0.03	0.02	--
Particleboard, 2 weeks old, 16 mm	0.15	0.43	0.05	0.03	--
Sawdust & shavings, dried, unresinated	0.06	0.19	0.04	0.02	--
Particleboard, 10 years old, 10 mm	0.04	0.11	0.13	0.08	--
Melamine film-coated PB, 14 mm	0.04	0.11	--	--	--
Melamine PB without film, 14 mm	0.03	0.09	--	--	--
Melamine-UF film-coated PB, 14 mm	0.04	0.16	--	--	--
Melamine-UF PB without film, 14 mm	0.02	0.05	--	--	--

Excerpted from: Sundin et al., 1992.

^a InterScan is a portable formaldehyde analyzer.

^b Chamber concentrations were measured at the Casco laboratory.

Table B-7. Percent of Higher Aldehydes (Hexanal) and Terpenes of Total VOC

Type of Material	Total VOC	Part of Total VOC			
		Aldehydes	Terpene	Misc.	Total
	μg/m ² -h	(%)	(%)	(%)	(%)
Hardboard, standard 3.2 mm	90	4	96	0	100
Hardboard, oil-treated 3.2 mm	80	6	94	0	100
Plywood, UF, 10 mm	150	8	25	67	100
MDF, UF, 16 mm	110	8	18	74	100
Lumber, planed, pine	920	1	81	18	100
Particleboard, UF 2 weeks old, 16 mm	430	32	22	46	100
Sawdust and shavings (pine, spruce)	190	27	20	53	100
Particleboard, UF 10 years old, 10 mm	110	6	19	75	100

Excerpted from: Sundin et al., 1992.

B.6 National Particleboard Association Study

A two-part preliminary study was conducted for the National Particleboard Association (NPA) to analyze product emissions from particleboard and medium-density fiberboard materials. The test objectives for the two laboratories participating in this two-part study were different with subsequent differences in the type of data that were reported. GEOMET Technologies performed the first analysis and prepared a report on emissions results from chamber analysis. The objective of the GEOMET study was to determine emissions from composite wood products from a target list of 26 VOCs (Table B-8). GEOMET evaluated TVOC, individual volatile organic compounds (IVOC), and formaldehyde emissions from 18 particleboard and fiberboard products. No data were provided for VOCs that were not on the target list.

Table B-8. NPA Target Compounds

Acetaldehyde	Hexanal
Acetone	Limonene
α -Pinene	m & p-Xylenes
Benzaldehyde	1-Nonanal
Benzene	Octanal
β -Pinene	o-Xylenes
Borneol	p-Cymene
Camphene	Pentanal
Ethylbenzene	Pentane
Heptanal	1-Pentanol
Heptane	Phenol
1-Heptanol	Toluene
2-Heptanone	trans-2-Octanal

Source: GEOMET, 1994.

Georgia Tech Research Institute (GTRI) performed the second analysis of a subset of the materials evaluated by GEOMET. The primary objective of the GTRI work was to determine if α -pinene and other terpenes were being emitted from composite wood products that were not detected in the GEOMET study. The GTRI evaluation reported all VOCs emitted from the composite wood products detected in the chamber air regardless of the source of the chemical. A major concern of the NPA with the GTRI data was the identification of unexpected VOCs detected during emissions tests. These unexpected VOCs included freons, chloroform, 1,1,1-trichloroethane, and benzene (Table B-9). According to GTRI, these unexpected VOCs resulted from contamination of the composite wood samples from sample containers. For simplicity, individual analyses comprising the NPA's two-part study are presented separately below.

Table B-9. Sample Container Contaminants

Acetone	Longifolene
Benzene	Pentanes
Bromodichloromethane	Thujone
Chloroform	Thujopsene
Geraniol	Toluene
Isoprene	Trichlorofluoromethane

Source: Personal communication, Mike Hoag, National Particleboard Association, November 16, 1993.

B.6.1 Part I - GEOMET

GEOMET specimens consisted of both finished and unfinished particleboard and MDF. Table B-10 summarizes these product test specimens. Test specimens, selected and prepared for evaluation by NPA, were delivered to GEOMET. Then, each specimen, with an area consisting of 0.0105 m² per side and a loading factor of 0.41 m²/m³, was conditioned for a 5-day period in the 0.052-m³ chamber. Following the conditioning period, separate air samples were collected at 24 hours for TVOC, at 24½ hours for IVOC, and at 25 hours for formaldehyde. This sample pattern was chosen because samples could not be taken simultaneously due to the low chamber flow rate (~0.87 L/min⁻¹). TVOC and IVOC air samples, which were collected in sorbent tubes, were analyzed with a GC. IVOC analysis included identification and quantitation of 26 target compounds. Formaldehyde concentrations for each specimen were determined using the Chromatropic Acid method (NIOSH 3500) and are listed in Table B-11. The detection limit for each of the specimens was 13.9 µg/m³, except for Specimen 1A for which the detection limit was 41.7 µg/m³.

Table B-10. Test Specimens

Specimen ID	Substrate
Unfinished PB 1A	Southern Yellow Pine
Unfinished PB 1B	Southern Yellow Pine
Unfinished PB 2A	Western Fir
Unfinished PB 2B	Western Fir
Unfinished PB 3A	Hardwood
Unfinished PB 3B	Hardwood
Unfinished MDF 4A	Medium-Density Fiberboard
Unfinished MDF 4B	Medium-Density Fiberboard
Finished PB 5A	Southern Yellow Pine
Finished PB 5B	Southern Yellow Pine
Finished PB 6A	Southern Yellow Pine
Finished PB 6B	Southern Yellow Pine
Finished PB 7A	Southern Yellow Pine
Finished PB 7B	Southern Yellow Pine
Finished PB 8A-1	Southern Yellow Pine
Finished PB 8A-2	Southern Yellow Pine
Finished MDF 9A	Medium-Density Fiberboard
Finished MDF 9B	Medium-Density Fiberboard

Source: GEOMET, 1994.

Specimens 1A through 4B were composed of various wood substrates without a finished surface. Specimens 5A through 9B were covered with various finishes using four different adhesives. Specimens 1A and 1B and Specimens 5A through 8B were all composed of southern yellow pine (SYP). A direct comparison was made between the TVOC concentration levels of the unfinished SYP substrate, Specimens 1A and 1B, to the finished SYP substrates, Specimens 5A through 8B. All of the finished specimens had lower TVOC concentration levels than the unfinished specimens, with the exception of the 120-hour analysis for Specimen 8A-2. Concentrations of the identified targeted organic compounds for the nine specimen pairs are shown graphically for specimens analyzed at 24 and 120 hours in Figure B-1. The reader is referred to the individual study for any additional information (GEOMET, 1994).

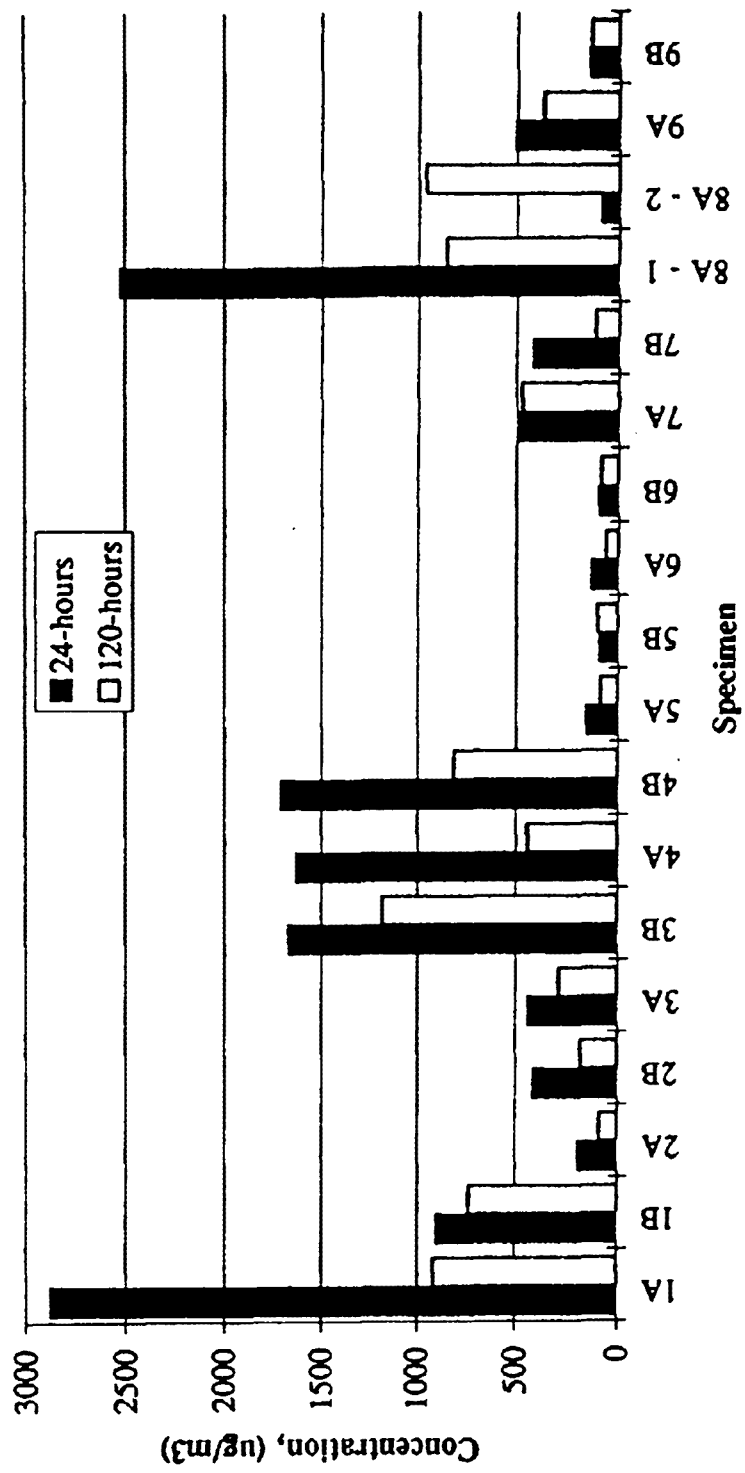


Figure B-1. TVOC concentrations (GEOMET, 1994).

Table B-11. Formaldehyde Emissions Data from Engineered Wood Products

Specimen	Concentration, $\mu\text{g}/\text{m}^3$	
	24 Hours	120 Hours
Unfinished PB (1A)	603	421
Unfinished PB (1B)	123	123
Unfinished PB (2A)	99	132
Unfinished PB (2B)	809	375
Unfinished PB (3A)	120	95
Unfinished PB (3B)	246	153
Unfinished MDF (4A)	183	175
Unfinished MDF (4B)	110	129
Finished PB (5A)	116	54
Finished PB (5B)	127	79
Finished PB (6A)	65	62
Finished PB (6B)	9	26
Finished PB (7A)	364	408
Finished PB (7B)	719	371
Finished PB (8A-1)	14	28
Finished PB (8A-2)	21	21
Finished MDF (9A)	140	153
Finished MDF (9B)	246	89

Compiled from: GEOMET, 1994.

B.6.2 Part II - GTRI

GTRI also prepared a report on emissions results from chamber analyses. GTRI evaluated TVOC emissions from 10 product specimens consisting of eight urea-formaldehyde bonded particleboards and two medium-density fiberboards. Compounds were identified and quantitated by comparisons to authentic standards, and basic emissions factors were calculated using procedures outlined in the standard method given in the Carpet Policy Dialogue Report (Leukroth, 1991). This method is a generally accepted method used to measure chemical emissions from dry products. Like carpet, the composite wood products tested had flat, dry surfaces and were allowed to offgas in a chamber.

Various organic compounds were identified. The primary organic compounds emitted were a variety of terpenes. The analyzed substrates were urea-formaldehyde-bonded particleboards,

except for two MDF specimens. Although not specifically stated by the author, one can assume that Specimen 6, an interior-grade MDF, was bonded with a urea-formaldehyde resin, which is typically used to bond composite wood products designed for interior use. Using the same logic, one can make a similar assumption that exterior-grade MDF, Specimen 7, was bonded with a phenol-formaldehyde resin, which is moisture-resistant and more appropriate for exterior use. Specimens 1 through 3 were analyzed for total and specified VOCs at 24 hours only. Specimen 10 emitted the highest levels of formaldehyde and TVOC. At 120 hours, the organic emissions for Specimens 9 and 10 were still increasing; however, the formaldehyde emissions for Specimen 10 were constant at 24 and 120 hours. The formaldehyde and acetaldehyde levels for Specimen 8 continued to increase at 120 hours while the TVOC levels decreased. Excluding Specimen 6, the acetaldehyde emissions for all the samples decreased significantly after 24 hours. Table B-12 lists formaldehyde emissions data from this study, both concentration and emissions rates, for Specimens 4 through 10 taken at 24 and 120 hours for seven of the boards in the GTRI analysis. Specimens 1 through 3 were not analyzed for formaldehyde. For additional information, the reader is referred to the original document (GTRI, 1993).

Table B-12. Formaldehyde Emissions Data from Particleboard and MDF

Specimen	Product Line	Concentration ($\mu\text{g}/\text{m}^3$)	Emissions Rate ($\mu\text{g}/\text{m}^2\text{-h}$)
4	11/16" Industrial	27.29 ^a	127.52 ^a
		20.54 ^b	95.98 ^b
5	5/8" Underlayment	50.26	237.08
		41.17	194.20
6	3/4" Interior (MDF)	9.66	44.72
		13.75	63.66
7	3/4" Exterior (MDF)	3.10	14.49
		3.29	15.37
8	5/8" Red Oakprint	18.78	88.58
		19.60	92.45
9	5/8" White Oakprint	c	c
		7.92	38.08
10	5/8" Particleboard	59.21	279.29
		59.00	278.30

Excerpted from: GTRI, 1993.

^a Sample taken at 24 hours for all top numbers in column.

^b Sample taken at 120 hours for all bottom numbers in column.

^c No data for sample.

Emissions of VOCs from Specimens 4 through 8 were lower at the 120-hour evaluation than they were at the 24-hour evaluation. However, VOC emissions from Specimens 9 and 10 increased at 120 hours. Figure B-2 graphically depicts TVOC emissions rates from each specimen. The reader should note that, due to contamination concerns, compounds identified as sample container contaminants (Table B-9) have been deleted from the TVOC emissions totals depicted in Figure B-2.

B.7 Thøgersen Study

A Scandinavian study (Thøgersen et al., 1993), showed that water-damaged chipboards result in substandard air quality due to increased formaldehyde emissions and microbiological growth. Nine chipboard specimens of identical dimensions (200 x 800 x 13 mm³) with untreated edges were placed in chambers, three specimens per chamber. The first specimen set was used as a reference specimen and was kept at constant standard conditions (21 ± 1 °C, 30 ± 15 percent RH, 15 ± 1 m/s air velocity, and 0.80 ± 0.05 L/s air supply) established by the researchers for the duration of the experiment. The second specimen set was submerged in a water bath for 24 hours and then placed in a special climate chamber without air change, maintaining 80 percent humidity for 6 days. Following simulated water damage and conditioning, specimen set 2 was placed in its chamber. Specimen set 3 was subjected to the same simulated water-damage process as specimen set 2. However, following the simulated water-damaging process, specimen set 3 was placed into its chamber for bakeout at a temperature (35 ± 1 °C) much higher than the reference temperature (percent RH, air velocity, and air supply were the same as the reference specimen).

Study investigators reported that, for the reference specimen, Specimen 1, the formaldehyde concentration decayed exponentially until it flattened to a steady state after 11 days. At this steady-state, the chamber concentration of formaldehyde for the reference specimen was about 0.01 mg/m³. Investigators stated that, during the decay phase, chemical substances diffused to the surface and evaporated; after emissions were stabilized, subsequent decomposition determined the emissions rate. The water-damaged specimens, both Specimens 2 and 3, which were wetted with water, had high emissions rates immediately following return to their respective chambers. The researchers assumed that the high emissions rates for water-damaged Specimens 2 and 3 were due to:

- Increased diffusion speed produced by higher water content
- Organic compounds transported into the air along with water evaporation
- Glue dissolution promoted by higher water content.

In spite of these high emissions rates, concentration levels for Specimens 2 and 3 decreased more rapidly than the concentration levels of the reference specimen. The rapid concentration decay was attributed to the lower total initial amount of formaldehyde present in the specimens after water damage. Researchers believed that some formaldehyde had been released during the simulated water-damage treatment. They also postulated that water-damage treatment caused

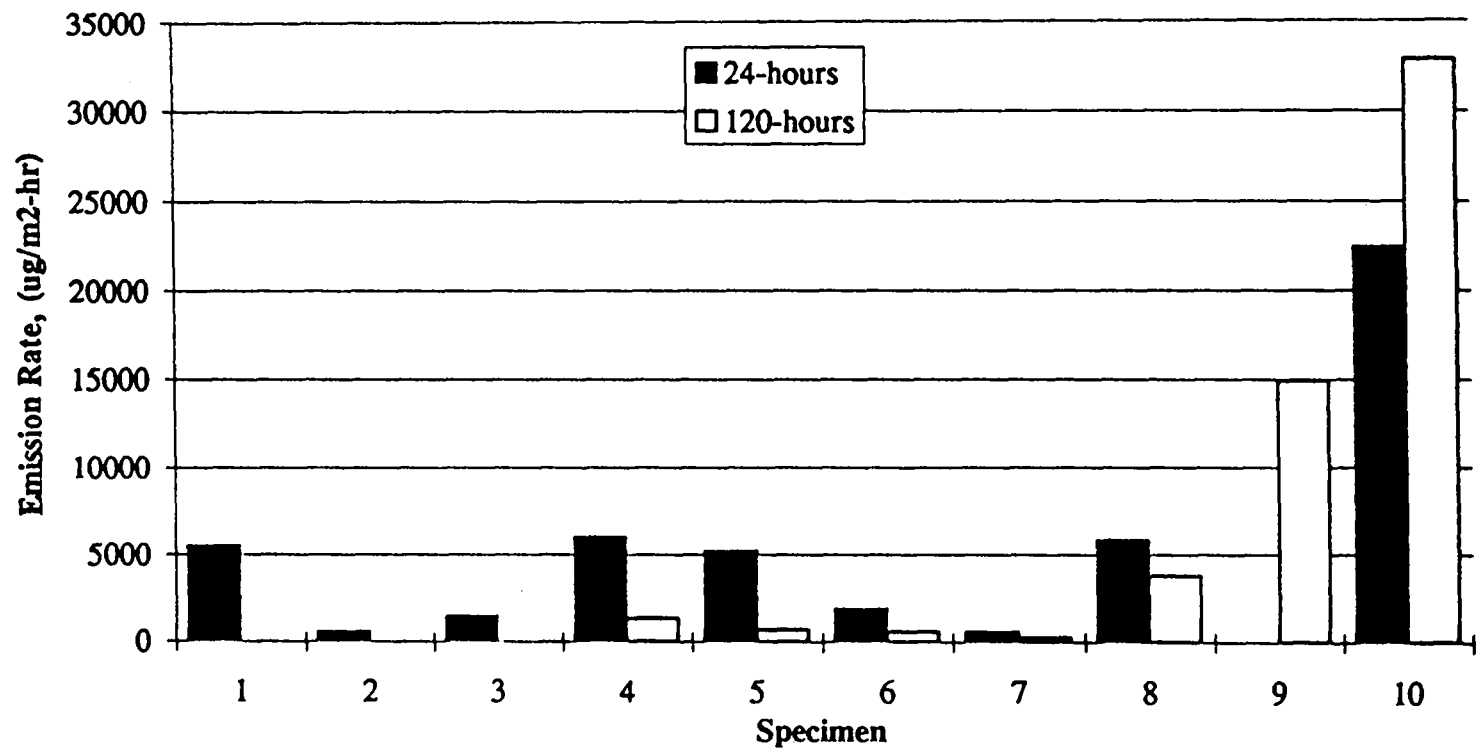


Figure B-2. TVOC emissions rates (GTRI, 1993).

considerable washout, which rarely occurs during a more gradual moistening, as occurs by diffusion or dripping in a real building. The bakeout specimen, Specimen 3, produced increased emissions during its bakeout period, but emissions soon steadied at a low rate. Researchers concluded that bakeout conditions should be maintained for several days to achieve a significant formaldehyde reduction to promote sufficient lasting effects.

When emissions were fairly steady from $t = 400$ h to $t = 500$ h, the mean chamber concentration of formaldehyde for the water-damaged Specimen 2 was about 0.0475 mg/m^3 . The mean formaldehyde concentration for Specimen 3, the water-damage specimen that underwent bakeout, was about 0.02 mg/m^3 . Comparing the formaldehyde concentrations for all three specimens at steady-state, the water-damaged specimen that did not experience bakeout had a formaldehyde concentration five times higher than the reference specimen. The water-damaged specimen that did experience bakeout appeared to have a formaldehyde concentration level twice that of the reference specimen (0.02 mg/m^3). Investigators stated that the small concentration difference between the reference specimen (0.01 mg/m^3) and the bakeout specimen (0.02 mg/m^3) could not be interpreted because both concentrations were close to the detection limit of the measuring instrument (0.06 mg/m^3).

The authors discussed only formaldehyde concentrations in this paper; however, they did state that TVOC concentrations conformed to curves similar to those describing formaldehyde concentration. Researchers concluded that water-damaged chipboards result in increased emissions of formaldehyde and other organic compounds, even when the chipboards dried, and that water-damaged chipboards result in less acceptable air quality when the chipboards are wet.

Microbiological samples were also collected and investigated as part of this study. Microbiological samples were collected by pressing agar plates to the chipboard specimens, and samples were then cultivated in a laboratory. The microbiological evaluation revealed significant growth of micro fungi after water damage. Ten species were identified, with the penicillium species dominating. Spores began growing when humidity was introduced, and the specimen contained spores even after drying. Following bakeout, spores were able to grow. The researchers added that, in a building, these spores can float through the air and adhere to material surfaces where they can grow under favorable conditions. Once established, these microorganisms are very difficult to eliminate. Total removal of infected materials is the only remedy when this type of growth occurs.