WOOD DUST

1. Exposure Data

1.1 Composition of wood

Wood is one of the world's most important renewable resources and grows in forests all over the world. Forests cover about one-third of the globe's total land area, about 3.4 million km^2. This area represents more than 1.0 trillion m^3 of total tree biomass; of this biomass, about 3.5 thousand million m^3 per year are harvested, about half of which is used as fuel, predominantly in developing countries. 'Industrial roundwood' (1.7 thousand million m^3/year) is the term applied to all sawn wood (54%), pulpwood (21%), poles, pit props (14%) and wood used for other purposes such as particle-board and fibre-board (11%) (FAO, 1992; Schulz, 1993).

The species of trees that grow and are harvested in different countries vary considerably. Hardwoods dominate, for instance, in Italy, where oak, chestnut and beech are important species (Haden-Guest *et al.*, 1956). In other, primarily colder regions, conifers dominate: for example, pine and spruce in the Nordic countries and pine, spruce, hemlock, cedar and fir in Canada. Table 1 shows trees harvested for industrial use by broad category (conifer versus non-conifer) in some of the countries in which epidemiological studies have been conducted on wood dust. Even within countries, however, there is considerable variation: in western United States of America, conifers, such as Douglas fir and Ponderosa pine, were of primary economic importance in the 1950s, while various non-conifers were important in the mid-west and north-east, and southern yellow pine was the single most important species in the south-east (Haden-Guest *et al.*, 1956).

Many countries with little domestic production of lumber, such as the Netherlands, import wood, and even countries with much domestic production import wood for specific uses: for example, Finland, which produces pine, spruce and birch, imports some tropical woods, such as mahogany and teak, for furniture production (Welling & Kallas, 1991). The data in Table 1 probably represent the species used in the logging, sawmill and pulp and paper industries, which usually consume wood from nearby regions. The species of trees used in different branches of the wood industry are described in sections 1.4.2–1.4.6. About two-thirds of all wood used in the world for industrial purposes is from softwood species (FAO, 1993).

1.1.1 Classification and nomenclature

The Earth has an estimated 12 000 species of tree, each producing a characteristic type of wood. Spermatophytes are subdivided into two classes on the basis of seed type: gymnosperms, which have exposed seeds, and angiosperms, with encapsulated seeds. These classes are further separated into orders, families, genera and species. As an illustration of the main divisions, the full classification of Scots pine (*Pinus sylvestris* L.) is given in Figure 1.

Table 1. Industrial roundwood[a] production in 1980 (thousands of cubic metres) by country

Country	Conifers	Non-conifers
Europe		
Denmark	1 185 (64%)	665 (36%)
Finland	38 010 (88%)	5 010 (12%)
France	14 069 (49%)	14 897 (51%)
Germany (western)	21 670 (74%)	7 657 (26%)
Italy	1 404 (28%)	3 705 (72%)
Netherlands	577 (72%)	228 (28%)
Norway	8 158 (96%)	316 (4%)
Sweden	40 000 (89%)	4 795 (11%)
United Kingdom	2 609 (68%)	1 232 (32%)
Former USSR	246 400 (89%)	31 300 (11%)
Asia		
China[b]	50 016 (63%)	29 186 (37%)
Japan	21 427 (63%)	12 624 (37%)
North America		
Canada	144 100 (93%)	10 124 (7%)
United States	246 525 (75%)	80 570 (25%)
Australia	4 009 (26%)	11 642 (74%)
New Zealand	9 698 (98%)	247 (2%)

From FAO (1993)
[a]All wood used for sawn wood and veneer logs, pulpwood, chips, particles, poles and pit props
[b] Estimates

Most species are deciduous trees or hardwoods, and only about 800 species are coniferous trees or softwoods (Bauch, 1975). Wood-producing tree-like plants, such as bamboo (*Graminaceae*) and palm (*Palmae*), differ from trees in that they lack secondary thickness growth.

The terms 'hardwood' and 'softwood' refer to the species of tree and not necessarily to the hardness of the wood. While hardwoods are generally more dense than softwoods, the density varies considerably within each family and the hardness of the two groups overlaps somewhat (Fengel & Wegener, 1989; see also Table 6). Gymnosperms comprise all trees that yield softwood lumber. Only one order, Coniferales, is important from the point of view of industrial use. The angiosperms are separated into two classes on the basis of initial seed leaf: monocots (e.g. bamboo and palms) have one initial seed leaf, and dicots (e.g. oak and birch) have two. Dicots comprise all tree-sized plants that yield hardwood lumber and occur mostly in temperate zones.

Figure 1. Classification of Scots pine

Class	Gymnospermae
	↓
Order	Coniferales
	↓
Family	Pinaceae
	↓
Genus	*Pinus*
	↓
Species	*Pinus sylvestris* L.

From Jane (1970)

The scientific and common names of some softwoods and hardwoods are given in Table 2.

Table 2. Nomenclature of some softwoods and hardwoods

Genus and species	Common name
Softwood	
Abies	Fir
Chamaecyparis	Cedar
Cupressus	Cypress
Larix	Larch
Picea	Spruce
Pinus	Pine
Pseudotsuga menziesii	Douglas fir
Sequoia sempervirens	Redwood
Thuja	Thuja, arbor vitae
Tsuga	Hemlock
Hardwood	
Acer	Maple
Alnus	Alder
Betula	Birch
Carya	Hickory
Carpinus	Hornbeam, white beech
Castanea	Chestnut
Fagus	Beech

Table 2 (contd)

Genus and species	Common name
Hardwood (contd)	
Fraxinus	Ash
Juglans	Walnut
Platanus	Sycamore
Populus	Aspen, poplar
Prunus	Cherry
Salix	Willow
Quercus	Oak
Tilia	Lime, basswood
Ulmus	Elm
Tropical hardwood	
Agathis australis	Kauri pine
Chlorophora excelsa	Iroko
Dacrydium cupressinum	Rimu, red pine
Dalbergia	Palisander
Dalbergia nigra	Brazilian rosewood
Diospyros	Ebony
Khaya	African mahogany
Mansonia	Mansonia, bete
Ochroma	Balsa
Palaquium hexandrum	Nyatoh
Pericopsis elata	Afrormosia
Shorea	Meranti
Tectona grandis	Teak
Terminalia superba	Limba, afara
Triplochiton scleroxylon	Obeche

From Vaucher (1986)

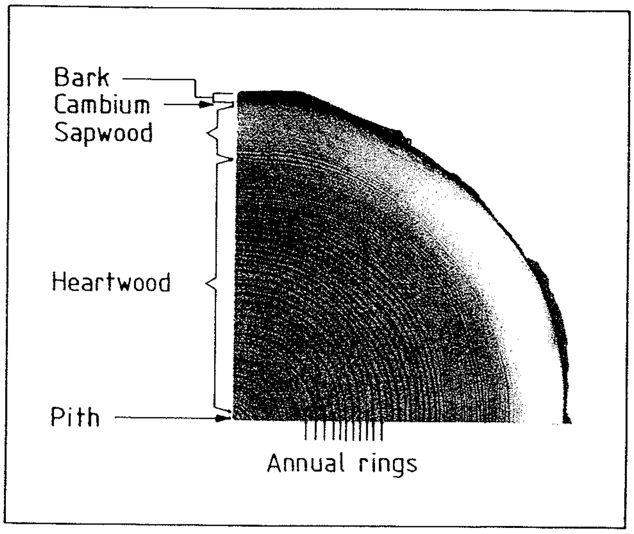
1.1.2 Anatomical features

Detailed information on wood anatomy is given by Jane (1970), Panshin and de Zeeuw (1970), Wagenführ and Scheiber (1974), Grosser (1977), Barefoot and Hankins (1982) and Hoadley (1990).

A look at the cross-section of a stem or a stem segment (Fig. 2) reveals a differentiation between bark and wood and, in many species, inner and outer areas with different coloration. Whereas some cells in the outer part (sapwood) are still alive (parenchyma), all cells in the inner part (heartwood) are dead. There is strong biosynthetic activity at the sapwood–heartwood boundary, where stored materials such as starch and other carbohydrates are transformed into low- and medium-relative-molecular-mass substances (extractives) and deposited in the heartwood (Streit & Fengel, 1994). It is assumed that these substances contribute to the conservation and protection of wood. The cells of wood tissue are produced in the cambium, a cell monolayer between the phloem (inner bark) and xylem (wood) (Fig. 2), where growth in length and thickness of a tree occurs.

The morphology of softwood tissue is simpler than that of hardwood tissue. Softwood consists, in its bulk, of only one cell type, tracheids, which are elongated, fibre-like cells with a square or polygonal cross-view. Less than 10% of the wood consists of short, brick-like parenchymal cells arranged radially. Moreover, some softwoods contain epithelial cells that secrete resin into canals which run horizontally and radially through the wood.

Figure 2. Segment of a stem showing the various macroscopically visible areas of wood

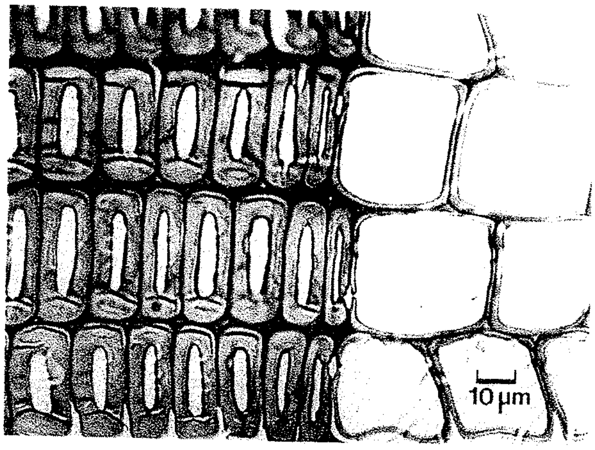


Adapted from Hoadley (1990)

Tissue formed in springtime (in temperate zones) is called 'earlywood' and consists of tracheids with wide lumina and thin walls (Fig. 3), which transport water from the roots to the top of the tree. Rows of valve-like openings (pits) at the ends of the tracheids allow exchange of water between adjacent cells. Tracheids produced in summertime ('latewood') have thick walls and small lumina; they serve predominantly to stabilize the tree.

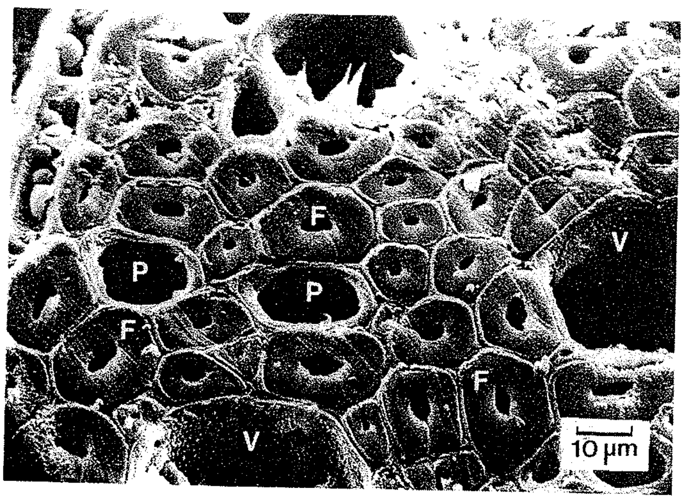
In hardwoods, there is more detailed differentiation between stabilizing, conducting and storage tissue. Stabilizing tissues contain libriform fibres and fibre tracheids, which are elongated cells with thick polygonal walls and small lumina (Fig. 4). The conducting system is composed of vessel elements fitted together to form long tubes of up to several metres. The vessels have thin walls and large diameters. At the junction of two elements, there are stiffening rings or plates with perforations characteristic of different wood species. Storage tissues consist of longitudinally and radially arranged parenchymal cells. Hardwoods that contain resin canals also have a secretory system of epithelial cells.

Figure 3. Border between latewood (left) and earlywood (right) in a softwood (spruce); light micrograph



From Fengel & Wegener (1989)

Figure 4. Hardwood tissue (beech) with vessels (V) and parenchymal cells (P) surrounded by libriform fibres (F); scanning electron micrograph



Adapted from Fengel & Wegener (1989)

1.1.3 Cell wall structure and distribution of components of wood

The walls of wood cells consist of various layers, which differ in structure and chemical composition (Fig. 5; Fengel & Wegener, 1989). The individual cells of wood tissue are glued together in the middle lamella, which consists mainly of lignin, polyoses and pectins. Often there is no exact, visible border between the pure middle lamella and the outer cell wall layer, which is called the primary wall and is formed by a net-like arrangement of cellulose fibrils (Fig. 5a) embedded in a matrix of lignin and polyoses. The middle lamella and primary wall are often called the 'compound middle lamella' (Fig. 5b).

The next layer is the secondary wall, which is subdivided into secondary walls 1 (S1) and 2 (S2). S1 and S2 contain densely packed cellulose fibrils arranged in parallel, which differ in the angle at which the fibrils run: in the S1, the fibrils run at a wide angle in relation to the fibre axis and in the S2, at a small angle. The S2 is the thickest wall layer and accounts for 50% (vessels, parenchymal cells) to 90% (tracheids, libriform fibres) of the whole cell wall. Parenchymal cells are equipped with a third secondary wall (S3) which has a fibril arrangement that is more open than that in the S2.

At the inner border of the cell wall, there is a final thin layer called the tertiary wall (T), in which the cellulose fibrils run at an angle similar to that of the S1. In some species, the tertiary walls of tracheids, fibres and vessels are covered with a wart-bearing amorphous layer (Fig. 5a,b).

The lignin content decreases from the compound middle lamella through the S2, while the cellulose content increases in the same direction (Table 3). The polyose content is highest in the S1, but because of the thickness of the S2, most lignin and polyoses are deposited in this layer.

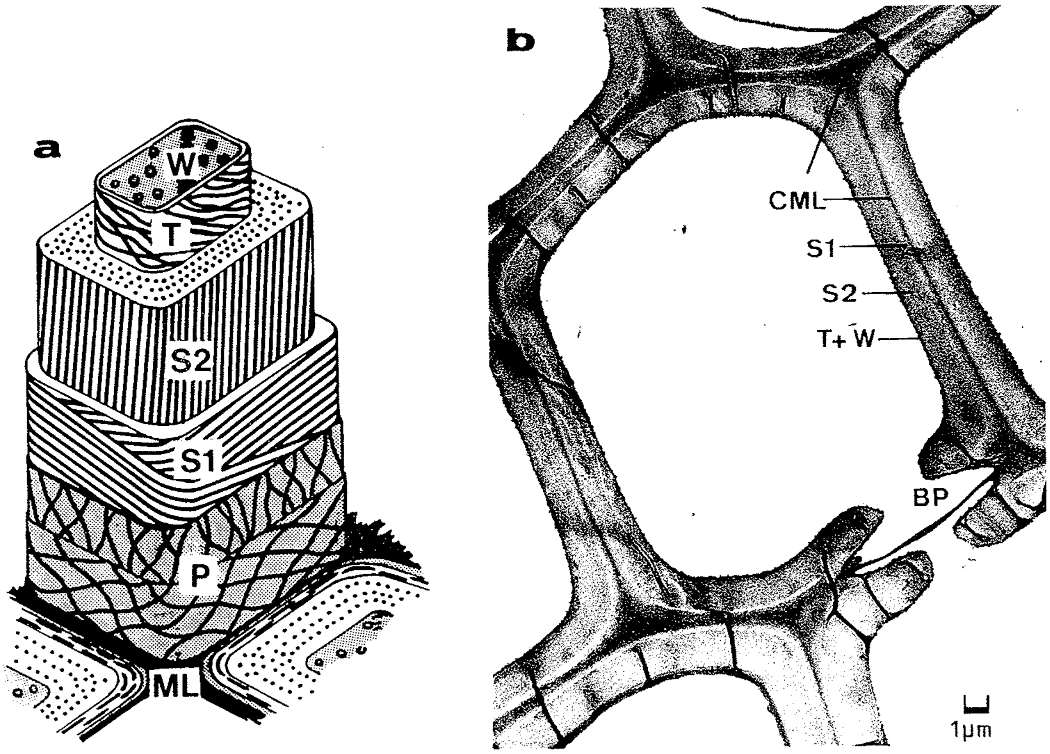
The 'extractives', the organic matter of wood, are found in the resin canals and parenchymal cells. In heartwood, extractives are also deposited in the compound middle lamella and the secondary walls. Trees with a high content also have extractives in the lumina (Fengel, 1989).

In areas where mechanical deformation of stems and branches has occurred, special tissues are found. In such 'compression areas' in softwood tracheids, the S2 is provided with helical cavities and contains a high percentage of lignin (compression wood). In hardwoods, fibres with a thick additional gelatinous layer consisting of relatively pure cellulose are formed in tension areas (tension wood). Compression and tension woods are together referred to as 'reaction wood' and may influence the processing of wood.

1.1.4 Chemical components

In this section, the main constituents of woods are identified and differences between hardwood and softwood are indicated. The formulae of a number of chemical constituents are shown in Figure 6. Chemicals found only in fruit or flowers or in fungi growing on trees are not described. Extensive reviews, with detailed accounts of numerous extractives, have been published (Beecher *et al.*, 1989; Fengel & Wegener, 1989; Swan, 1989). Hillis (1987) specifically reviewed heartwood.

Figure 5. Cell wall structure



From Fengel & Wegener (1989)

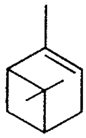
(a) Model of a vascular cell (softwood tracheids, hardwood libriform fibres); (b) cross-section of a softwood tracheid (umbrella fir) with a bordered pit (BP); transmission electron micrograph. ML, middle lamella; P, primary wall; S1, secondary wall 1; S2, secondary wall 2; T, tertiary wall; W, warty layer; CML, compound middle lamella (ML + P)

Table 3. Approximate content of lignin, cellulose and polyoses in the cell wall layers of softwood tracheids

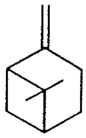
Wall layer	Lignin (%)	Cellulose (%)	Polyoses (%)	Main polyoses
Compound middle lamella	60	15	25	Pectins, galactan, xylan
Secondary wall 1	30	35	35	Xylan, mannan
Secondary wall 2 + tertiary wall	25	60	15	Mannan

From Fengel & Wegener (1989)

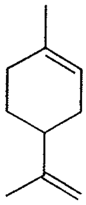
Figure 6. Chemical formulae of certain chemical components of wood



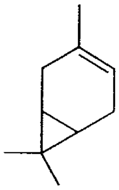
(1a)
α-Pinene



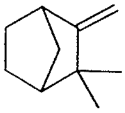
(1b)
β-Pinene



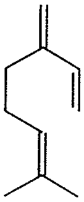
(2)
Limonene



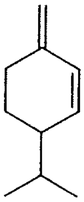
(3)
Δ³-Carene



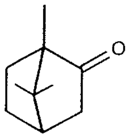
(4)
Camphene



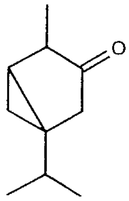
(5)
Myrcene



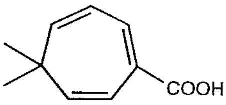
(6)
β-Phellandrene



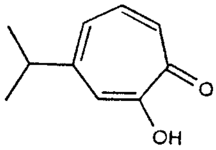
(7)
Camphor



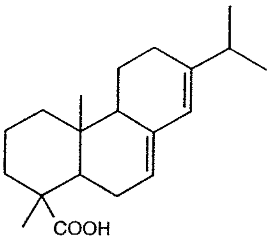
(8)
Thujone



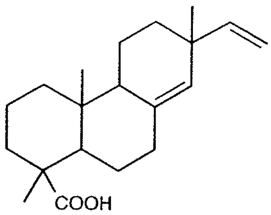
(9)
Thujic acid



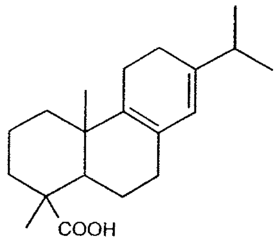
(10)
β-Thujaplicin



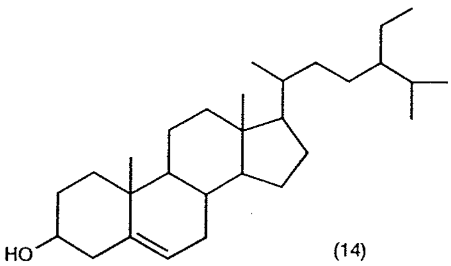
(11)
Abietic acid



(12)
Pimaric acid

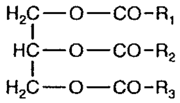


(13)
Palustric acid



(14)
β-Sitosterol

Figure 6 (contd)



(15)
Fats and Oils

$H_3C—(CH_2)_n—CO—O—(CH_2)_m—CH_3$

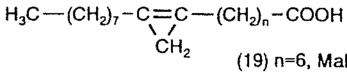
(16)
Waxes

$H_3C—(CH_2)_n—COOH$

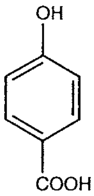
(17)
Fatty acids

$HO—(CH_2)_m—CH_3$

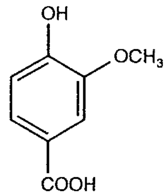
(18)
Fatty alcohols



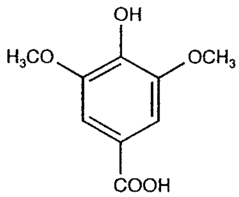
(19) n=6, Malvalic acid
(20) n=7, Sterculic acid



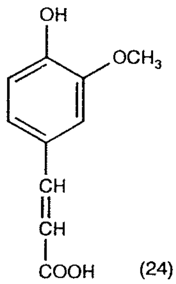
(21)
para-Hydroxy-
benzoic acid



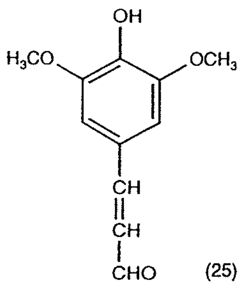
(22)
Vanillic acid



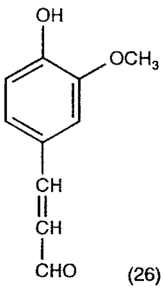
(23)
Syringic acid



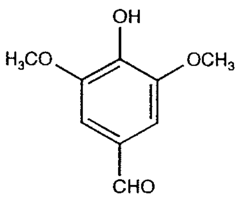
(24)
Ferulic acid



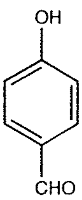
(25)
Sinapaldehyde



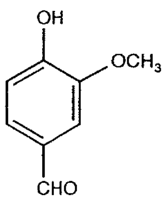
(26)
Coniferyl aldehyde



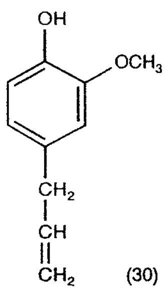
(27)
Syringaldehyde



(28)
para-Hydroxy-
benzaldehyde

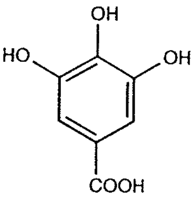


(29)
Vanillin

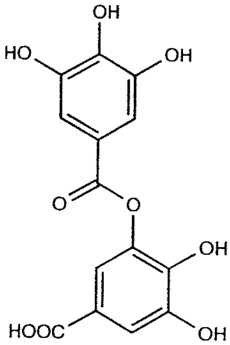


(30)
Eugenol

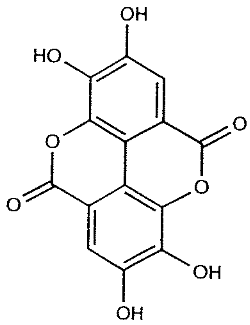
Figure 6 (contd)



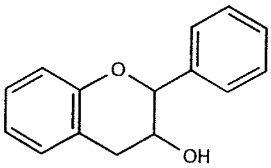
(31)
Gallic acid



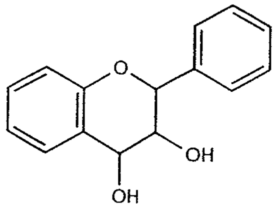
(32)
Digallic acid



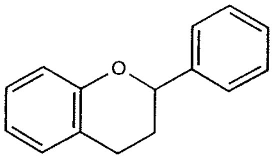
(33)
Ellagic acid



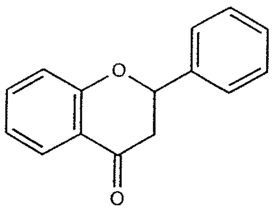
(34)
Flavan-3-ol



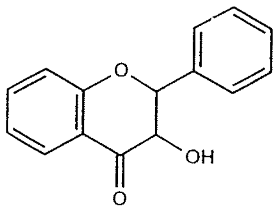
(35)
Flavan-3,4-diol



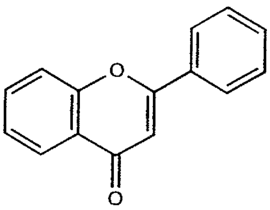
(36)
Flavanes



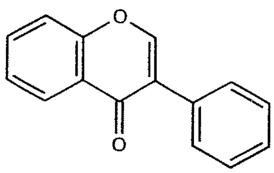
(37)
Flavanones



(38)
Flavanonols

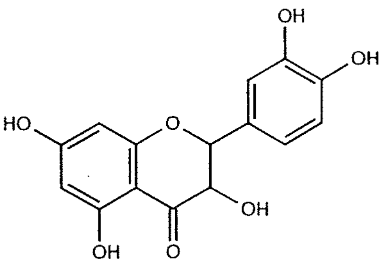


(39)
Flavones

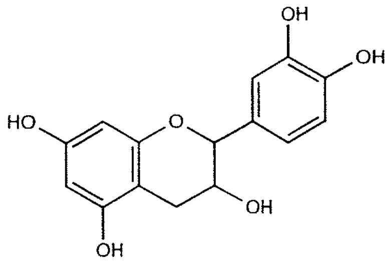


(40)
Isoflavones

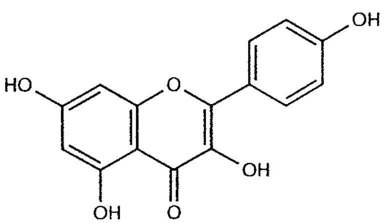
Figure 6 (contd)



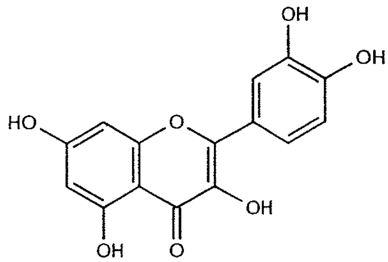
(41)
Taxifolin



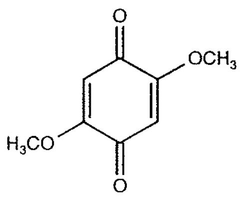
(42)
Catechin



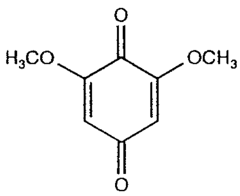
(43)
Kaempherol



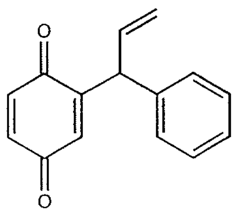
(44)
Quercetin



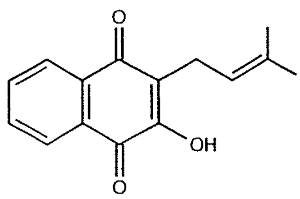
(45a)
2,5-Dimethoxy-
benzoquinone



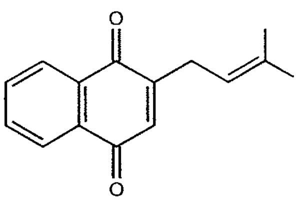
(45b)
2,6-Dimethoxy-
benzoquinone



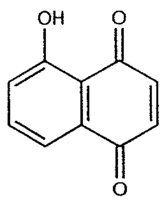
(46)
Dalbergione



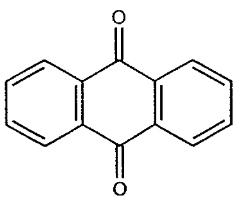
(47)
Lapachol



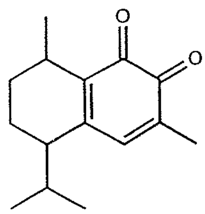
(48)
Desoxylapachol



(49)
Juglone

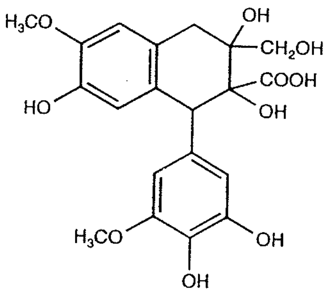


(50)
Anthraquinones

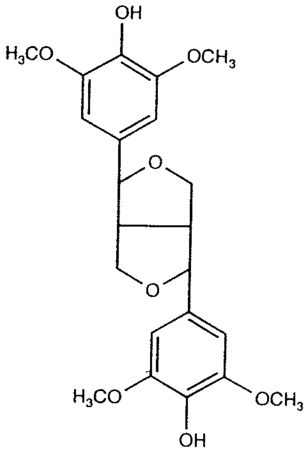


(51)
Mansanone A

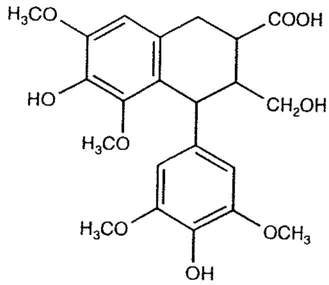
Figure 6 (contd)



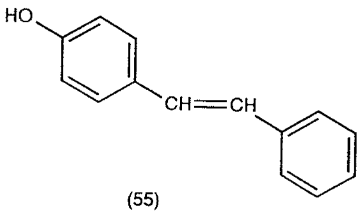
(52)
Plicatic acid



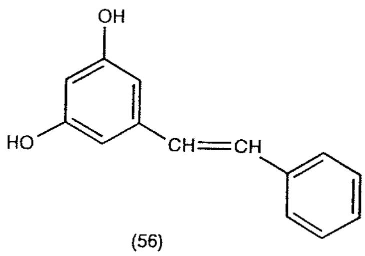
(53)
Syringaresinol



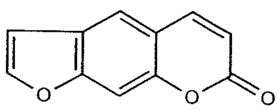
(54)
Thomasic acid



(55)
4-Hydroxystilbene



(56)
Pinosylvin



(57)
Psoralen

(a) Macromolecular components

The essential chemical constituents of wood are cellulose, polyoses (hemicelluloses) and lignin, which has a macromolecular structure. Although cellulose is the uniform structural element of all woods, the proportions and chemical composition of lignin and polyoses differ in softwood and hardwood. Wood generally also contains small amounts of polymeric compounds, such as starch, pectic substances and proteins.

Cellulose is the major component (40–50%) of both softwood and hardwood. It can be briefly characterized as a linear high-relative-molecular-mass polysaccharide built up exclusively of D-glucose units joined by β(1→4)glycosidic linkages.

Polyoses (hemicelluloses) are present in larger amounts in hardwood than in softwood and differ in their sugar composition. They are composed mainly of five neutral sugar units—the hexoses, glucose, mannose and galactose, and the pentoses, xylose and arabinose. Some polyoses also contain uronic acid units. The molecular chains of polyoses are much shorter than those of cellulose and are branched and/or contain side groups. Softwood has a higher proportion of mannose units and more galactose units than hardwood; hardwood has a higher proportion of xylose units (Table 4).

Table 4. Non-glucosic sugars in polyoses of some woods (%)

Species	Mannose	Xylose	Galactose	Arabinose	Uronic acid	Rhamnose
European spruce	13.6	5.6	2.8	1.2	1.8[a]	0.3
Scots pine	12.4	7.6	1.9	1.5	5.0	NR
European beech	0.9	19.0	1.4	0.7	4.8[a]	0.5

From Fengel & Wegener (1989); NR, not reported

[a]4-*O*-Methylglucuronic acid

Lignin, the third macromolecular component of wood, is quite different from the polysaccharides. The monomers of lignin are phenylpropane units joined by various linkages, resulting in complicated three-dimensional macromolecules. The lignin content of softwood is higher than that of hardwood, and softwood and hardwood lignins differ structurally and with regard to their contents of guaiacyl, syringyl and *para*-hydroxyphenyl units. Most softwood lignins are typical guaiacyl lignins containing minor amounts of syringyl and *para*-hydroxyphenyl units. The composition of lignin varies much more in hardwood than in softwood, and hardwood lignins have higher proportions of syringyl units. The syringyl content of typical hardwood lignins varies between 20 and 60%.

(b) Low-relative-molecular-mass components

A heterogeneous mixture of organic and inorganic compounds occurs in different species of wood in various amounts. The organic matter that can be extracted from wood with nonpolar or polar solvents is commonly called 'extractives'; the inorganic part is reduced mainly to ash in the analysis of wood. The 'extractives' represent 0.1–1% of the wood mass in trees of temperate zones and 15% or more in tropical wood. As some of these compounds protect against injury or attack from fungi, insects and bacteria, they may have toxic, irritant or sensitizing properties.

Organic extractives can have aliphatic, alicyclic or aromatic structures. Non-polar extractives comprise mainly terpenes, fatty acids, resin acids, waxes, alcohols, sterols, steryl esters and glycerides. The polar extractives of wood generally consist of aromatic (phenolic) compounds, i.e. tannins, flavonoids, quinones and lignans. The common water-soluble extractives of wood are carbohydrates and their derivatives, alkaloids, proteins and inorganic material. Hardwood tends to have a higher percentage of polar extractives than softwood (see section 1.3.2 (*a*) and Table 7).

(i) Terpenes and terpenoids

Terpenes are a ubiquitous group of natural compounds, of which over 4000 have been isolated and identified. They can be derived from isoprene (2-methyl-1,3-butadiene) units, which are usually connected to form one or more rings. Two or more isoprene units build up the mono-, sesqui-, di-, tri-, tetra- and polyterpenes.

The extractives of softwood include all classes of terpenes, whereas hardwoods contain mainly higher terpenes. Monoterpenes are found only in some hardwood tropical species, while the volatile oil (turpentine) of softwoods consists mainly of these compounds. The commonest are α- and β-pinene (Fig. 6, **1a, 1b**) and limonene (**2**) (see IARC, 1993), which are present in all softwoods; but Δ^3-carene (**3**), camphene (**4**), myrcene (**5**) and β-phellandrene (**6**) are also widespread. α-Pinene has been suggested to be a sensitizing agent, and terpenes with a keto group (e.g. camphor (**7**) and thujone (**8**)) appear to be more toxic than related compounds.

The tropolones, structures with seven-membered rings, are considered to be derivatives of monoterpenes. Compounds such as thujic acid (**9**) and β-thujaplicin (**10**) are found only in species of the *Cypressaceae* family. Sesquiterpenes are found in many tropical woods but are quite rare in hardwood in temperate zones and in softwood.

The diterpenes seem to be restricted to softwood species and occur mainly in the form of resin acids. They are mostly tricyclic compounds, such as abietic (**11**), pimaric (**12**) and palustric acids (**13**). The neutral diterpenes consist of hydrocarbons, oxides, alcohols and aldehydes.

A great variety of triterpenes are present in many hardwoods in tropical and temperate zones and also in softwoods. Most have a steran substructure and must therefore be assigned to the steroids. The main component of the steroid group in both softwood and hardwood is β-sitosterol (**14**). Some saponins, which are glycosides of triterpenes and steroids, cause dermatitis and other diseases.

(ii) Fats, waxes and their components

Although saturated and unsaturated higher fatty acids are found in wood mostly as esters with glycerol (fats and oils (**15**)) or with higher alcohols (waxes (**16**)), they also occur in free form (**17**). Free and combined fatty acids typically include linoleic, palmitic (**17**: n=14) and stearic acid (**17**: n=16) and some cyclopropenic acids, such as malvalic (**19**) and sterculic (**20**) acid. The corresponding fatty alcohols (**18**) are also found. Triglycerides dominate the glycerides (fats), as compared with mono- and diglycerides, especially in hardwood species.

(iii) Phenolic compounds

Extracts of woods contain low-relative-molecular-mass phenols. Some are probably degradation products of compounds such as lignin, which may be hydrolysed during several extractions or during steam distillation. These simple phenols are represented in hardwood predominantly by acids (including *para*-hydroxybenzoic (**21**), vanillic (**22**), syringic (**23**) and ferulic acids (**24**)) and in both softwood and hardwood by aldehydes (including sinapaldehyde (**25**), coniferyl aldehyde (**26**), syringaldehyde (**27**), *para*-hydroxybenzaldehyde (**28**), vanillin (**29**) and eugenol (**30**) [see IARC, 1985a]).

The extractives of wood also contain various compounds with phenolic substructures, including tannins, flavonoids, quinones, lignans and stilbenes.

Tannins: Tannins can be separated into hydrolysable and condensed types (phlobaphenes). The hydrolysable tannins are esters of gallic acid (**31**) and its dimer (digallic acid (**32**)) and of ellagic acid (**33**) with monosaccharides, mainly glucose. They may be subdivided into gallotannins, which yield gallic acid, and ellagitannins, which yield ellagic acid upon hydrolysis. The main components of condensed tannins are catechin derivatives (flavan-3-ol (**34**)) and leucoanthocyanidin derivatives (flavan-3,4-diol (**35**)). Tannins can precipitate proteins and influence cell metabolism.

In general, tannins are found mainly in hardwoods, although they may also occur in the heartwood of certain softwoods (conifers) that contain condensed tannins. Hydrolysable tannins (gallic acid type) occur less frequently than condensed tannins in hardwoods and are found predominantly in oak, chestnut and eucalyptus. All other woods, particularly tropical woods, contain mainly condensed tannins (catechin type). An overview of tannin chemistry is presented by Hemingway and Karchesy (1989).

Flavonoids: Condensed tannins belong to the large group of extractives known as flavonoids, which comprise the subgroups flavanes (**36**), flavanones (**37**), flavanonols (**38**), flavones (**39**) and isoflavones (**40**). They have various numbers of hydroxyl and methoxyl groups on the aromatic rings, either as glycosides or aglycones. The large number of flavonoids is due not only to the degree of saturation of the heterocyclic ring but also to the variation in degree of hydroxylation of the rings. The colour of some heartwoods is a result of the presence of flavonoids and related compounds. These compounds also occur more frequently in hard- than softwood, although several flavonoids, such as taxifolin (**41**) and catechin (**42**), have also been identified in softwood. Other flavonoids found in hardwood are kaempherol (**43**) (see IARC, 1983a) and quercetin (**44**) (see IARC, 1983b).

Quinones: A range of aromatic quinones is present in extracts of various woods, including substituted benzoquinones (2,5- (**45a**) and 2,6-dimethoxybenzoquinone (**45b**), dalbergione (**46**)), various naphthoquinones (lapachol (**47**), desoxylapachol (**48**), juglone (**49**)) and anthraquinones (**50**) and their derivatives, such as quinoid sesquiterpenes (mansonone A (**51**)). They are responsible for the strong colours, high durability and dermatitic properties of some woods. Dimethoxybenzoquinone has been found in extracts of about 50 wood species.

Lignans: Lignans consist of two β–β-linked phenylpropane units. Some are dimeric structures that are also present in the lignin molecule. Lignans are typical heartwood components and occur in small or negligible amounts in sapwood. Although they are often found in softwood (e.g. plicatic acid (**52**) in western red cedar), some occur in hardwood, including syringaresinol (**53**) and thomasic acid (**54**), particularly in alder, oak and elm species.

Stilbenes: Stilbenes occur especially in the heartwood of both softwood and hardwood. These compounds, e.g. 4-hydroxystilbene (**55**) and pinosylvin (**56**), are responsible for the photosensitive reactions that cause darkening of woods.

(iv) Miscellaneous organic compounds

Free amino acids and their linked structures (proteins) are also found, but in small amounts. A high protein content encourages the development of wood-destroying organisms. Some hardwood species, particularly many tropical woods, also contain alkaloids of various chemical structures, including very toxic compounds such as berberine and strychnine. Phototoxic compounds belonging to the furocoumarin group, such as psoralen (**57**) and its derivatives, occur in some tropical wood species. Table 5 includes some biologically active compounds found in wood.

(v) Inorganic compounds

The main inorganic components of wood are potassium, calcium and magnesium; silicon is found in some tropical woods (Fengel & Wegener, 1989). These components comprise 0.2–0.5% of wood in temperate zones but often much more in tropical woods. Potentially carcinogenic inorganic elements such as chromium have been found in very small amounts in some wood species (Saka & Goring, 1983).

Table 6 summarizes several characteristics of softwoods and hardwoods; these are generalizations to which there are specific exceptions. Some characteristics are the same for softwoods and hardwoods; for others, the ranges among species overlap; and for a few characteristics, there are marked distinctions.

1.2 Wood-related industries and occupations

Workers in a wide variety of industries may be exposed to wood dust. In this section, the main industries and occupations in which such exposure may occur and the steps in the processes used are described (see also Koch, 1964; Maloney, 1977; FAO, 1981; IARC, 1981; Darcy, 1984; Industrial Accident Prevention Association, 1985; McCammon *et al.*, 1985; Holliday *et al.*, 1986; Suchsland & Woodson, 1986; Clayton Environmental Consultants, 1988; Williston, 1988). Detailed descriptions are generally provided only for processes that result in wood dust. The history of woodworking processes in the sawmill, furniture and construction industries was reviewed previously (IARC, 1981) and is not repeated here; however, major changes in processes that occurred during this century and affect exposure to wood dust are discussed.

Table 5. Examples of biologically active organic compounds found in wood

Substance class	Compound	Wood type
Terpenes	α-Pinene	Softwood
	Δ^3-Carene	Softwood
	Camphor	Softwood
	Thujone	Softwood
	β-Thujaplicin	Softwood
	Sesquiterpene lactones	Softwood/hardwood
	Abietic/Neoabietic acid	Softwood/hardwood
	Saponins	Hardwood
Phenols	Coniferyl aldehyde	Softwood/hardwood
	Sinapaldehyde	Hardwood
	Eugenol	Softwood/hardwood
	3-(Pentadecyl)catechol	Hardwood
	5-(Pentadec-10-enyl)resorcinol	Hardwood
Tannins	Catechin derivatives	Hardwood
	Leucoanthocyanidin derivatives	Hardwood
Flavonoids	Kaempherol	Hardwood
	Quercetin	Hardwood
Quinones	2,5- and 2,6-Dimethoxybenzoquinone	Softwood/hardwood
	3,4-Dimethoxydalbergione	Hardwood (tropical)
	Lapachol	Hardwood
	Desoxylapachol	Hardwood
	Juglone	Hardwood
	Mansonone A	Hardwood (tropical)
Lignans	Plicatic acid	Softwood
Stilbenes	2,3′,4′,5′-Tetrahydroxystilbene	Softwood
	Chlorophorin	Softwood
	Pinosylvin	Softwood
Miscellaneous	Alkaloids (berberin)	Hardwood
	Furocoumarins (psoralen)	Hardwood (tropical)

From Hausen (1981), Henschler (1983) and Swan (1989)

Table 6. Comparison of softwoods and hardwoods

Characteristic	Gymnosperms/conifers/ softwoods	Angiosperms/deciduous wood/hardwoods
World production of industrial roundwood (1980) (× 1000 m^3)	990 000	450 000
Density (g/cm^3)	White (silver) fir: mean, 0.41 (0.32–0.71) European spruce: mean, 0.43 (0.30–0.64) Scots pine: mean, 0.49 (0.30–0.86)	European beech 0.68 (0.49–0.88) European oak 0.65 (0.39–0.93)
Fibres	Long (1.4–4.4 mm)	Short (0.2–2.4 mm)
Cell type	One (tracheids)	Various
Cellulose	~40–50%	~40–50%
Unit	β-D-Glucose	β-D-Glucose
Fibre pulp	Long	Short
Polyoses	~15–30%	~25–35%
Units	More mannose More galactose	More xylose
Lignin	~25–35%	~20–30%
Units	Mainly guaiacyl	Mainly syringyl or guaiacyl
Methoxy group content	~15%	~20%
Extractives content		
Non-polar (e.g. terpenes)	High	Low
Polar (e.g. tannins)	Low	High

From Fengel & Wegener (1989)

1.2.1 Major woodworking processes

(a) Debarking

Debarking is the mechanical removal of bark from a log and is performed in sawmills and other mills where logs are first processed. Debarking can be done in a number of ways: in wood-to-wood abrasion, the pounding and friction of logs against each other in a rotating drum removes the bark; in the 'flail' method, chains pound against the log to loosen the bark; in peripheral milling, logs are rotated against knives. Bark can also be removed by pressing tool points against the log to loosen the bark and then using a ring debarker or high-pressure water jets. In general, debarking involves little or no exposure to wood dust, because the wood is 'green' (fresh) and thus has a high moisture content. Furthermore, the main goal of the operation is to leave the wood intact.

(b) Sawing

Saws are used to cut logs or large pieces of wood into appropriate sizes for further modification and use. Sawing is performed by drawing a blade with a series of sharpened teeth through the wood. As with many woodworking machines, the amount of wood dust generated by mechanical sawing operations is influenced by the speed of the sawing action, the angle of cutting relative to the wood grain and the sharpness and width of the blade. Sawing against the wood grain (cross-cutting) is more likely to shatter wood cells than sawing lengthwise (ripping). Sharp, thin blades produce less wood dust by volume because the kerf, the cut made in the wood, is narrower, but the particle sizes are also likely to be smaller.

The simplest saws are blades with a series of teeth along one edge and a handle on one or both ends; they are powered by a human operator or operators, who move the blade back and forth. Almost all saws used for commercial purposes are mechanically operated. In recent decades, high-energy jets and lasers have been introduced, which generate less wood dust but are not in broad commercial use. The commonest types of mechanical saws are described below.

(i) Band saw

The blade of a band saw is a continuous metal strip with teeth on one or both edges which rotates around two wheels. Band saws are used in many wood industries, from sawmills to wood product manufacturing and can be powered by steam, hydraulic or electric mechanisms.

(ii) Circular saw

The blade of a circular saw is a rigid metal disk with teeth along its circumference which cuts as it rotates. Circular saws are also used in many wood industries. A table saw is a circular saw with the blade protruding through a table; a radial arm saw is a circular saw suspended above the working surface on a movable armature.

(iii) Sash gang saw

In a sash gang saw (frame saw), a series of parallel blades (a gang) fixed between two vertical members (a sash) are drawn up and down to rip boards being moved through the saw on rollers. These saws are used almost exclusively in sawmills to cut large pieces of lumber lengthwise in order to create a set of boards. Circular saws are also commonly used for gang sawing.

(iv) Jig saw

A jig saw has a short, rigid blade attached to a reciprocating mechanism to cut with an up-and-down motion. Jig saws are used in many wood products industries and can be both hand-held and stationary.

(v) Chain saw

A chain saw has a continuous articulated chain with teeth along its outer edge. It is generally powered by a gasoline engine and is used almost exclusively in logging, although it may sometimes be used as a cut-off saw in sawmills.

(c) Sanding

Sanding is smoothing the surface of wood, 'an abrasive process in which sharp edges of small, hard, crystalline particles are rapidly drawn across the surface of the wood with pressure being applied perpendicular to the surface' (Holliday *et al.*, 1986). The abrasives used include carborundum, emery, glass and pumice. The smaller the abrasive particles, the finer the dust produced; and the faster the sander, the greater the volume of dust produced. Sanding is done in many wood industries, with small, hand-held sanders or generally larger stationary machines. Sanders can range in size from hand-held to large drums or belts for smoothing a full panel. The commonest types of sander are the belt sander, a continuous strip of sandpaper rotated around two rollers; the disk sander, a circular piece of sandpaper fastened to a rotating disk; the drum sander, a continuous strip of sandpaper rotated on a drum; and the orbital sander, which operates with an elliptical, vibrating motion.

(d) Planing, jointing, moulding and shaping

Planing, jointing, moulding and shaping are milling processes. A planer is used to smooth one or more sides of a piece of wood and at the same time to reduce it to a predetermined thickness. The planer head is made up of a series of cutting blades mounted on a cylinder, which revolves at high speed. The operation is generally performed parallel to the wood grain.

A jointer is a machine for squaring and smoothing the edges of lumber or panels. Jointers are used especially in preparation for glueing and in other situations in which a smooth surface is needed. Jointers vary in size from small, hand-held devices to large, stationary machines. A jointer is similar to a planer in its operation, but its blades are generally smaller, and it is designed to smooth or true a surface rather than to change the thickness of a board.

Moulders are used to cut and shape mouldings. They generally consist of a top cutter head, followed by two sideheads and by a bottom cutterhead. The cutterheads are staggered spindles of various designs. Shapers are similar to moulders, but are used to cut and shape the outer sides of wood boards and products. Shapers generally consist of a table through which protrudes a rotating spindle with blades shaped to produce the desired contour. Shapers can be used to cut the edge designs found on furniture and picture frames and in many other applications, such as wooden model making.

(e) Turning (lathing)

Turning involves use of a lathe to produce cylindrical shapes in wooden objects. One end of the piece of wood is fixed to a clamp or plate, which is rotated. The point of operation is a tool point or a long knife, which has a cutting, scraping or shearing action (depending on the angle of contact) when applied against the wood. Some lathes rotate the piece quickly while the tool or knife remains stationary and in continuous contact until the desired shape is formed; other lathes rotate the piece slowly and have a peripheral milling cutterhead.

(f) Boring (drilling), routing and carving

Boring machines are designed to drill holes for dowel joists, screws and other purposes. They are similar to drills and drill presses used for other materials and contain rotating bits of various designs. Routers are used to shape the edges and corners of wooden objects and to cut slots of various shapes; a spindle is suspended over the piece, and the process combines aspects of boring and milling. Carving machines are rotating tools mounted on spindles, which are designed for both side and end cutting.

(g) Mortising and tenoning

A mortise is a cavity cut into a piece of wood to receive a tenon (a protrusion), which together form a mortise–tenon joint. Mortises are of various shapes and can be formed by different machines. The commonest is the hollow chisel mortiser, which forms a rectangular mortise with a hollow chisel or shell, inside of which are a rotating boring bit or bits. The bits cut the hole, which is squared by the sharp edges of the chisel. Chain mortisers, similar in design to chain saws, and oscillating bit mortisers, which are specialized routers, can also be used. Tenoning machines are also of various designs, involving both milling and sawing actions. End matchers are tenoning machines used to create both the tongue and groove for hardwood flooring.

(h) Veneer cutting

A rotary peeler is a lathe-like machine used to cut veneers, thin sheets of wood, from whole logs using a shearing action. The log is rotated against a pressure bar as it hits a cutting knife to produce a thin sheet of 0.25–5 mm in thickness. The logs used in this process may be softened before use by soaking in hot water or steaming. The edges of the sheet are usually trimmed with knives attached to the pressure bar. Veneers are used as decorative laminates or for the manufacture of plywood. Because the moisture content is high, very little wood dust is usually generated by this process.

(i) Chipping, flaking, hogging and grinding

Chippers, sometimes known as 'hackers' in Europe, are generally large rotating discs with blades embedded in the face and slots for chips to pass through. The chips are produced when logs or mill wastes are introduced to the blades by inclined gravity feed, horizontal self-feed or controlled power feeding. Generally, the cutting action of the chipper is perpendicular to the blades, and different designs are used for whole logs and for slabs and edgings. Although the term 'chipping' is sometimes used to refer to related processes, such as flaking and hogging, the end product is quite different. Chippers are used in many industries to reduce logs and wood waste to uniform-sized chips for pulp, reconstituted board and other uses.

Flaking machines convert wood into flakes for use as the raw material for particle-board, flake-board and wafer-board. They may be similar in design to a chipper, except that the wood must be fed to the flaker with the grain orientated parallel to the knives. Peripheral milling designs are also used. Wafers are generally made directly from logs that have been stored in a holding pond using a waferizer, a machine containing a series of rotating knives which peel thin wafers (Holliday *et al.*, 1986). Water-saturated wood is best for these processes, and, because the wood must be orientated, short logs are often used. Because the moisture content is high and the wood is orientated, less dust is generated than is commonly the case with chipping.

Hogs are used to reduce pieces of wood and residues into chips for use as fuel or for other purposes in which a uniform size is not required. Hogging machines are of various designs, including knife-type hogs, with rotating cylinders bearing protruding knives, rotating disks with progressively smaller teeth, and hammer mills, with rapidly revolving 'hammers' that cut the wood by impact. Hogging produces chips of maximal size but not of uniform shape or size.

Grinding is used to reduce wood chips to the consistency of flour. Hammer mills and grinding plates are used to pulverize or grind the wood, and the resulting product is sifted to control the size. Wood flour can be used for a ground cover or animal bedding or as a sweeping compound, filler or extender for composition boards and plastics, depending on the size of the particles. As the wood used for this process is generally dry, exposure to dust in uncontrolled settings is high.

(j) Mechanical defibrating

A mechanical defibrator is a grinding machine used to break wood down into fibres for wood pulp and various types of fibre-board. The wood must have a high moisture content; species such as spruce and fir are preferred because of their light colour, uniform structure and high fibre content. Short logs are forced against a grindstone, made of natural stone or of artificial stone composed of silicon carbide or aluminium oxide. The stone is showered with water to remove the pulp and cool the surface. Little or no exposure to wood dust should occur during this wet process.

1.2.2 Sawmilling

The raw materials for sawmills are supplied by the forestry and logging industries. Workers responsible for cutting down trees (felling), sawing felled trees into log lengths (bucking), trimming off branches and clearing brush are most likely to be exposed to wood dust. Sawing and cutting are usually performed with chain saws, although axes, hand saws and malls (metal wedges) may also be used. Trailer-mounted chipping or hogging machines may be used at logging sites. As wood that is sawn and chipped has a very high moisture content, the particles of dust generated are likely to be large. Trees may also be sheared with hydraulic mechanisms mounted on logging tractors; in general, little dust is produced during the shearing of fresh wood. Although other logging workers, such as those involved in yarding and loading, may be exposed to wood dust, such exposures would probably be low.

Sawmills vary greatly in size, and operations are performed outdoors or indoors depending on the size of the mill and the climate of the region. The smallest sawmills are mobile or portable units consisting of a circular saw, a simple log carriage and a two-saw edger powered by a diesel or gasoline engine and operated by two to four workers (FAO, 1981). The largest mills are permanent structures, have much more elaborate, specialized equipment and may employ more than 1000 workers. A representative production line and various phases of work at a typical Scandinavian sawmill were described previously (IARC, 1981). The equipment in sawmills varies considerably with the age and size of the mill and the type and quality of boards produced.

After transport to a sawmill, logs are stored on land, in bodies of water adjacent to the mill or in ponds constructed for the purposes. The first process is debarking; as the wood is green or has been stored in water, little wood dust is produced. This process has been described as 'messy' rather than dusty, as earth, mould and fungus particles may adhere to the surface of the bark (Holliday *et al.*, 1986).

A cut-off saw, usually a circular saw or a very large chain saw, is used to even up the ends of the trunks before primary breakdown (the first phase of sawmilling) at a headrig. The headrig is a large stationary circular or bandsaw used to cut the log longitudinally. The log is transported to the headrig on a travelling carriage, which can rotate the log 90 or 180° and carries it back and forth through the headrig. Multiple band headrigs may also be used, especially for smaller logs, so that only a single pass may be needed (Williston, 1988). The products of the headrig are a cant (the square centre of the log), a series of slabs (the rounded outer edges of the log) and, in some cases, large boards. In secondary breakdown (or 'resaw'), the cant and large boards are further processed into usable sized boards. In small mills, a circular or band saw may be used; in larger mills, the cant and large boards are generally processed with gang saws of either the sash, circular or band saw type. Boards are cut to the proper width with edgers consisting of at least two parallel saws and to the proper length with trim saws. Edging and trimming can be done with circular or band saws; in some cases, chain saws are used for trimming. Exposure to wood dust may occur in all these operations, but the concentration varies greatly, depending on the distance from the point of operation and whether or not the worker is operating the saw from an enclosed booth (Teschke *et al.*, 1994).

In many mills, the slabs and other waste wood are chipped. Chipping is generally a separate process, but in some cases a chipper may be integrated into the headrig to increase efficiency (Williston, 1988). Wood chips and sawdust may be sold for pulp or used for reconstituted board manufacture, landscaping, fuel and other uses. Exposure to wood dust may occur during chipping.

After breakdown, the boards are sorted according to dimensions and grade and then stacked by hand or machine to await drying, also referred to as seasoning. At this point, fungicides may be applied, either by dipping single boards or bundles or by various spraying procedures, to prevent the growth of fungi on the sap which stain the surface of the wood blue (Kauppinen & Lindroos, 1985).

Cut lumber is either dried in the open air or, more commonly, in various types of kilns, including serial compartment and high-temperature kilns and continuous kilns, in which stacked bundles can move in a perpendicular or parallel position and the air movement is perpendicular or parallel to the boards. Exposure to wood dust is generally low in these operations.

Either before or after drying, the wood is marketable as a green or rough lumber; however, for most industrial uses, it must be processed further. Lumber is cut to its final size and surfaced in a planing mill, usually simultaneously on two sides of the board; planers that operate on all four sides may be called matchers. Moulders are sometimes used to round the edges of the wood. Exposure to wood dust may occur during planing and moulding, because the wood is dry and the aim of the operations is to produce a relatively smooth surface. Dust control systems, such as local exhaust ventilation, may be present in these operations; however, their effectiveness in controlling exposures is not certain (Teschke *et al.*, 1994).

After processing, wood is sorted, stacked and bundled in preparation for shipping. Workers may be exposed to wood dust during these operations, especially if no measures have been taken to remove dust after surfacing operations.

1.2.3 Manufacture of plywood and other boards

Plywood, particle-board and other boards consist of wood components of varying sizes, ranging from veneers to fibres, held together by an adhesive bond. The simplest of these boards are created in two steps: generation of the components, directly from whole logs or, for some products, from woodworking waste or non-commercial or low-value tree species; and their recombination into sheets with chemical resins or, in the case of wet process fibre-board, 'natural' bonding. These steps may be carried out at different locations, especially when woodworking waste is used. The manufacture of plywood, particle-board, wafer-board, strand-board, insulation board, fibre-board and hard-board are all relatively new industries which first became commercially important during this century, especially since the 1940s. For example, although techniques for making plywood have existed for many centuries, the term 'plywood' did not enter common usage until the 1920s (Maloney, 1977).

(a) Plywood manufacture

The term 'plywood' is used for panels consisting of three or more veneers that have been glued together. Plywood can be made from either softwood or hardwood. Veneers are usually created directly from debarked whole logs by rotary peeling; decorative veneers can be created by slicing a cant with a pressure arm and blade in a manner similar to peeling. The veneers are used either for manufacturing plywood or as decorative laminates for particle-board and other reconstituted boards. After peeling or slicing, the veneers are collected on long, flat trays or rolled onto reels and are then clipped into usable lengths with a guillotine-like machine and dried by artificial heating or natural ventilation. The dried panels are inspected and, if necessary, patched with small pieces or strips of wood and formaldehyde-based resins. If the dried veneers are too small, they can be spliced together by applying a liquid formaldehyde-based adhesive to the edges, pressing the edges together and applying heat to cure the resin. As the wood used to produce veneers is wet and the peeling and clipping operations do not generally produce much dust, relatively little exposure to wood dust occurs during these operations (Holliday *et al.*, 1986).

Plywood panels are produced by placing veneers that are roller- or spray-coated with formaldehyde-based resins between two unglued veneers. The plies are then stacked perpendicular to each other with respect to grain and transferred to a hot press, where they are subjected to pressure and heat in order to cure the resin. They are then cut to the proper dimensions with circular saws and surfaced with large drum or belt sanders. Additional machining may be done to give the plywood special characteristics.

The highest exposures to wood dust during the production of plywood occur in sanding, machining and sawing. Sanding can produce particularly large amounts of dust, since as much as 10–15% of the board may be removed during surfacing (Holliday *et al.*, 1986). These processes are now generally enclosed or done with local exhaust ventilation.

(b) Manufacture of particle-board and related boards

Particle-board (chipboard), flake-board, strand-board and wafer-board are made from chips of wood of various sizes and shapes using similar processes. Wafer-board and strand-board are made from very large particles—wood shavings and strands, respectively—and are used primarily for structural applications. Particle-board and flake-board are made from smaller wood chips and are often used to make wood-veneered and plastic-laminated panels for the manufacture of furniture, cabinets and other wood products. Most elements are made directly from logs, branches and mill waste.

The processes used for making reconstituted panels are generally the same. The elements must be sorted by size and grade and then dried, by artificial means, to a closely controlled moisture content. The dried elements are mixed with an adhesive (a phenol–formaldehyde or urea–formaldehyde resin) and laid out in mats. The mats are cut into sections, generally with a circular cut-off saw. The panels are formed into sheets by curing the thermosetting resin in a hot press and are cooled and trimmed to size. If necessary, sanders are used to finish the surface; drum sanders were used earlier, but wide belt sanders are now generally used (Maloney, 1977). Most sanders are enclosed, and large-capacity air systems are necessary to remove the dust generated. Reconstituted boards that are to be covered with a wood veneer or plastic laminate must be sanded, and surface coatings may be applied.

Reconstituted panels are made from either hardwood or softwood. Exposure to wood dust may occur during processing but varies greatly with the moisture content of the wood and the nature of the process. The highest exposures may occur during chipping and grinding of dried wood, and high exposures occur during cutting and finishing of panels, especially in sanding operations, if engineering controls are not in place or functioning properly.

In recent decades, a new industry has emerged to produce reconstituted lumber for various structural uses, such as beams, supports and other weight-bearing elements. While the manufacturing processes used may be similar to those used for making particle-board, isocyanate-based resins are used to add strength.

(c) Fibre-board manufacture

Fibre-boards are panels consisting of bonded wood fibres. The fibres are made by reducing (pulping) short logs or wood chips in a manner similar to that used for producing pulp for the paper industry (see IARC, 1981). A mechanical (groundwood) pulping process is usually used, in which chips are soaked in hot water and then ground mechanically. A wet or a dry process may be used to bond the fibres and create the panels. The wet process, based on paper production, was developed first; the dry process, which stems from particle-board techniques, was developed later. In the wet process, a slurry of pulp and water is distributed on a screen to form a mat, which is pressed, dried, cut and surfaced. The boards created by wet processes are held together by natural adhesive-like wood components and the formation of hydrogen bonds (Suchsland & Woodson, 1986). The dry process is similar, except that the fibres are distributed on the mat after addition of a binder (a thermosetting or thermoplastic resin or a drying oil) which forms a bond between the fibres. Fibre-boards vary greatly in density. Hard-board (high-density fibre-board) and medium-density fibre-board can be produced by wet or dry processes, while insulation board (low-density fibre-board) can be produced only by the wet process.

Fibre-boards can be made from either softwoods or hardwoods. Hardwoods generally make better hard-board, while softwoods make better insulation board (Suchsland & Woodson, 1986). Exposure to wood dust in the fibre-board industry may occur during debarking, cutting of logs to size and chipping (if these are not performed elsewhere) or the handling of wood chips before pulping. The processes involved in pulping have a chemical effect on the groundwood and some of the lignin and extractive materials may be removed; the dust generated during cutting of fibre-board and finishing operations may therefore differ from unprocessed wood dust (Holliday *et al.*, 1986).

1.2.4 Wooden furniture manufacture and cabinet-making

Traditionally, furniture is made from solid wood, and many different tree species have been used. Common species include hardwoods, such as sycamore, birch, oak, hickory, cherry, beech, ash and walnut, tropical woods such as mahogany, ebony and teak, and softwoods such as pine, fir, redwood, cedar and larch (Darcy, 1984). In this century, veneer- and plastic-covered chip-board and fibre-board panels have been used increasingly for the manufacture of cabinets, table tops and similar products. Solid hardwoods and hardwood-veneered panels are used for high-quality furniture because of the attractive patterns formed by their grains. In the furniture factories of the High Wycombe area of England, mainly beech, ash and elm are used for making tables and chairs, while elm, ash, veneered chip-board and fibre-board are used for cabinets and similar products (Jones & Smith, 1986).

The wooden furniture industry includes a wide variety of woodworking and non-woodworking operations. Various phases of the production of furniture and cabinets were described previously (IARC, 1981). In order to examine patterns of exposure to wood dust in the furniture industry in High Wycombe, Jones and Smith (1986) identified three stages of furniture production during which exposure may occur: conversion, component making and assembly. Although manufacturing processes vary by country and type of furniture produced, these three stages, sometimes under different names, generally occur in most facilities.

The 'conversion' stage is also referred to as rough milling, rough sizing or breakdown, when rough lumber is cut into the standard sizes needed for further machining. A variety of sawing and planing operations are performed during this stage (Darcy, 1984; Jones & Smith, 1986), usually with stationary machines. The wood used for furniture must generally be well seasoned (dried), and some facilities have kilns to further lower the moisture content before sawing and planing. Wood waste may be reduced with a hogger or chipper. Exposure to wood dust may occur during sawing, planing and chipping. Because of the nature of the operations, exposures should not be high, but if local exhaust ventilation is not used exposure to wood dust could occur.

The second stage, 'component making', is also referred to as machining or machine room operations. The converted pieces of lumber are cut to finished sizes and machined into the components (arms, legs, tops, sides) needed to make furniture. Some sawing and planing is done; in particular, bandsaws are used to shape pieces roughly before machining. To produce a variety of end-products, different milling machines are used, including jointers, routers, moulders, shapers, tenoners, lathes, boring machines and carving machines. The components may also be sanded, using brush, belt and drum sanders. Exposure to wood dust may occur during sawing, machining and sanding, although use of stationary machines and local exhaust ventilation may reduce exposure. If control measures are not used or are ineffective, however, exposure could be high. While most furniture is produced with machines, some workshops (in Italy and Spain, for example) produce traditional furniture or furniture that resembles antiques using many manual operations (IARC, 1981).

The final stage of production is 'assembly', when the components are put together. The potential source of wood dust at this stage is sanding, usually after assembly, which is often done with hand-held power tools. Dust control is more difficult for such operations. Although sanding was commonly performed at this stage in the English furniture industry, resulting in high exposures (Jones & Smith, 1986), assembled furniture may not require sanding.

Although the operations described above are the main sources of wood dust in the furniture industry, workers with other duties are also potentially exposed. Cleaning and maintenance workers may be exposed while removing dust from a work area or cleaning machinery or ventilation equipment. Their degree of exposure is directly related to the methods used to remove the dust; wet methods and vacuuming produce little dust, while sweeping and brushing may result in exposure, and the use of compressed air to blow off dust can result in high exposures. Assemblers, material handlers and other non-woodworkers, such as glue and upholstery workers, may be exposed if they perform their duties while the wood is still dusty. The furniture industry typically includes many operations in which there is little or no exposure to wood dust because a clean surface is needed for the operation to be effective. These operations include staining, varnishing, lacquering and painting. Generally, workers employed in these operations have little exposure to wood dust. In some situations (e.g. small factories and shops), workers may be employed in multiple phases of production.

French polish is a solution consisting of shellac dissolved in methanol. 'French polishers', however, not only apply this solution but sand down the surface after each coat has dried; the operation may be repeated tens of times. They were classified in the same category as stainers, sprayers and spray polishers in the study of Acheson *et al.* (1984) and were placed in the middle exposure category in the analysis.

Cabinet-making is a skilled trade closely related to furniture making. Cabinet-makers are highly skilled workers who are trained to operate a variety of woodworking machines and use various hand tools to fabricate and repair high-grade furniture. They may also be responsible for finishing surfaces with paints, stains and varnishes and for installing hardware, such as hinges and handles, and for other non-woodworking tasks. Cabinet-makers work in a variety of settings, from large furniture factories to small cabinet-making shops. They may also be employed in the construction industry to build, install and repair cabinets and other furniture and fixtures in both new and existing structures.

1.2.5 Manufacture of other wood products

Other products that may be manufactured from wood are musical instruments, sports equipment, kitchen utensils, wooden boxes, toys, rifle stocks, smoking pipes, coffins, doors and sashes, boats, mobile homes, wooden pallets, flooring, railroad ties, barrels and kegs, prefabricated structures, crates and fences. Exposure to wood dust varies according to the processing operations used, the type of wood used and other factors discussed in sections 1.2.1 and 1.4.1. The type of wood used is related to the use of the product; for example, products such as flooring, parquetry, baseball bats and tool handles are often made from hardwoods for aesthetic reasons and because of their durability. Doors, frames, panels and toys are often made from softwoods because of the ease with which these woods can be cut and machined.

The stages of production in which exposure to wood dust may occur can be categorized in the same way as for the wooden furniture industry in England (Jones & Smith, 1986): an initial phase mainly of machine sawing and planing to convert rough lumber into the sizes needed for further machining; an intermediate phase to cut the pieces of lumber to final size, machine and sand them; and a final stage to assemble the components, which may be sanded as part of the finishing. There is considerable variation between industries. For example, wooden pallets are made from rough lumber and require only sawing and assembly; or the final product of some industries may be a component for another industry, such as the stock for a rifle or the face of a clock. Wooden boats and other products that may be subjected to harsh environmental conditions are sometimes constructed of woods that are naturally resistant to environmental degradation, such as cypress, cedar and teak.

In some of these industries, exposures may be similar to those in the construction industry (see below). For example, the manufacture of prefabricated structures and mobile homes is very similar to construction carpentry, except that the operations are generally performed within an enclosed space. As in the construction industry, softwood is often used for framing and other structural purposes.

1.2.6 Construction, carpentry and other wood-related occupations

(a) The construction industry

Carpenters and joiners are skilled woodworkers employed extensively in the construction industry. Carpenters are responsible for the construction, erection, installation and repair of wooden structures and fixtures. Joiners are usually involved in the finer aspects of construction and the finishing of buildings. Carpenters use various saws, planers and chisels to perform their tasks, while joiners use a wider variety of tools and may perform some of their work away from the building site. The line between these two trades, which had separate guilds during the Middle Ages, is not always clear, however, and they may differ between countries. For example, in the United States, carpenters perform both types of tasks, while in France there is a greater distinction between carpenters and joiners. The term 'finish carpenter' is sometimes used to refer to workers who specialize in installing wooden trim, stairs and floors and other finishing operations.

Woodworking in the construction industry differs from that in the manufacturing industry, in that carpentry and some aspects of joinery are usually carried out at building sites, where conditions are constantly changing and hand tools are still used extensively. These two factors make it difficult to control or monitor exposures. When work is done outdoors, natural ventilation may lower the potential exposure, although operations such as sanding may still result in high exposures to wood dust. Construction-related woodwork carried out in shops with stationary equipment generates exposures to wood dust and other materials that are similar to those in other wood product industries.

Construction involves excavation, building foundations, framing, electrical installation, plumbing, roofing and finishing. Carpenters and other woodworkers may be involved in at least three of these steps: building foundations, framing and finishing. They may be responsible for constructing wooden forms for concrete foundations for both wooden and metal structures, either at the construction site or by prefabrication, from plywood and other reconstituted boards that have been specially treated with light petroleum oils (see IARC, 1989a). The framing of wooden structures involves the preparation, trimming and assembly of the various pieces of wood that comprise the weight-bearing members of a structure, including the roof timbers, beams, floor joists, wall sections, staircases and supports. This work is commonly performed on-site, although the pieces may be pre-cut and, in some situations, pre-assembled off-site. Softwoods, often pine, are most commonly used for beams, trusses, joists and studs, although hardwoods, such as oak, chestnut and elm, may also be used. Reconstituted wood products are often used for walls and underflooring. Wood that has been treated with preservatives, such as chromated copper arsenate (see IARC, 1987a) and chlorophenol derivatives (see IARC, 1986, 1987b), may be used for external walls and in other situations where the wood may be exposed to adverse conditions. A variety of saws and planers may be used, as well as simple hand tools such as chisels and hammers. Exposure to wood dust is rarely high during framing; however, insulation work performed at the same time as framing may involve exposure to insulating materials (see e.g. IARC, 1988).

Carpenters, joiners and other woodworkers, such as cabinet-makers, floor layers and parquetry workers, may be involved in finishing wooden and non-wooden structures, which involves installation of floorboards, staircases, door and window frames and sashes, moulding, cabinets and panelling of structures. Circular saws of various kinds, including table saws and radial arm saws, bandsaws, sanders of various kinds, including hand-held belt and rotary sanders, planers, routers, moulders and tenoners are commonly used. Hardwoods, softwoods, tropical woods and reconstituted panels are all used in finishing. Finishing generates the greatest potential exposure to wood dust, because sanding is done frequently, often in partly or fully enclosed spaces. Sanding, and particularly the sanding of floors, can result is high exposures to wood dust, and such operations are often carried out by workers who do not have adequate protection to avoid respiration of the dust.

(b) Maintenance and repair

Carpenters and joiners may also be responsible for the maintenance and repair of wooden structures and fixtures in industries varying from the services to manufacturing. Their exposures are similar to those of wooden construction workers, except that the work is more commonly performed indoors and may include other exposures. Although the terms 'carpenter' and 'joiner' are usually associated with the construction and maintenance trades, they are used in many industries to refer to skilled woodworkers. The term 'joiner' is also used in boat building and repair to refer to skilled workers who fabricate, assemble, install or repair wooden furnishings in ships and boats. Carpenters who work on wooden boats and ships are also referred to as 'shipwrights'.

(c) Pattern and model making

Wooden pattern makers plan, lay out and construct wooden units or sectional patterns, such as those used in forming sand moulds for casting. Wooden model makers construct precision models of products or parts used in mass production. Both pattern and model makers are highly skilled workers, who are employed by small shops or directly by mass production industries. Pattern and model making are not, however, mass production operations: each piece is made individually, starting from blueprints and ending with a finished product which must often meet very close tolerances. These workers use hand tools, measuring instruments and woodworking machinery such as bandsaws, lathes, planers, routers and shapers and a variety of hard, soft, tropical and laminated woods. The raw material used depends on the intended use; for example, in the United States automobile industry, softwoods are often used for experimental models, while harder and laminated woods are used for models that require more exact, stable dimensions (McCammon *et al.*, 1985).

(d) Wood shop teachers and artists

Exposure to wood dust may occur in a number of other occupational settings, including the teaching of woodworking, wood sculpture and design secondary schools, technical schools and universities. In such classes, a variety of woodworking machinery may be used in largely unregulated environments, under health and safety conditions that would not be acceptable in an industrial setting. For example, Lucas and Salisbury (1992) reported that the equipment used by a design materials class in a university art department included a planer, table saw, jointer, lathe, belt sander and band saw and many portable power tools. While the stationary machines had local exhaust ventilation, the fabric bag dust collector was located inside the classroom. Although students may be exposed intermittently, teachers may spend many hours per day in the same setting. Artists who create wooden sculptures and artisans making wooden objects may work under similar conditions.

1.3 Analytical methods

1.3.1 Characterization and measurement of wood dust

Wood dust and exposures to wood dust are characterized in several ways that affect the nature of exposures in woodworking industries: by type of wood, as airborne dust concentrations, by particle size distribution and by other parameters.

(a) Type of wood

Wood dust is frequently described by wood species or as hardwood or softwood (see section 1.1). Wood dust is also characterized by its moisture content: Dry wood (moisture content less than about 15–20%) is less elastic than moist (green) wood, and woodworking operations with dry wood result in a larger volume of total dust and a higher percentage of inhalable dust particles (Hinds, 1988).

(b) Airborne dust concentrations

(i) Total dust measurements

The parameter most commonly used to characterize exposures to wood dust in air is total wood dust concentration, in mass per unit volume (usually mg/m^3). Standard gravimetric methods for measuring total dust concentrations, such as NIOSH Method 0500 (Eller, 1984a), have been used routinely. In this general method, a known volume of air is drawn through a special membrane filter contained in a plastic cassette with a sampling pump. The dust concentration is calculated from the change in weight of the filter divided by the volume of air sampled, with a detection limit for personal sampling of wood dust of about 0.1 mg/m^3. Polyvinyl chloride filters are preferred for sampling wood dust because of its highly variable moisture content. Filters are environmentally equilibrated before and after sampling to avoid spurious effects from differential moisture uptake (Eller, 1984a; Holliday *et al.*, 1986; Sass-Kortsak *et al.*, 1989; Teschke *et al.*, 1994).

The cassette holding the filter is either open- or closed-faced during sampling. In the closed-faced mode, a cap with a 4-mm hole is placed over the 37-mm cassette face to protect the filter. Closed-faced operation is usually recommended when total suspended particulates are being measured (see, for example, United States Occupational Safety and Health Administration, 1993). Beaulieu *et al.* (1980) reported, however, that the open-faced filter collected 30–60% more dust (by weight) than the closed-faced filter, and they suggested that particles larger than about 10 μm are collected very inefficiently in the closed-faced configuration, as corroborated subsequently in other studies (Clayton Environmental Consultants, 1988; Hinds, 1988). Other authors have cautioned against the collection of particles 'too large to be inhaled' (Darcy, 1984) which would contribute disproportionately to the total weight of dust (Hounam & Williams, 1974). As an alternative, the United Kingdom Health and Safety Executive recommends a sampling head with seven 4-mm holes, the sampling characteristics of which appear to approximate current definitions of inhalable dust (Jones & Smith, 1986; United Kingdom Health & Safety Executive, 1989; Hamill *et al.*, 1991; Pisaniello *et al.*, 1991).

(ii) Particle size-selective measurements

A number of methods have been used to measure, more or less selectively, exposures to wood dust in the respirable particle size range (Hinds, 1988). NIOSH Method 0600 (Eller, 1984b) is intended for measurement of general 'respirable dust' concentrations. The equipment used is the same as that for NIOSH Method 0500, except that air is sampled through a 10-mm nylon cyclone (centrifugal separator) designed to accept 50% of unit density spherical particles of 3.5 μm aerodynamic diameter. Another standard technique, the horizontal elutriator (gravitational separator), is designed to collect a respirable particulate fraction defined by the British Medical Research Council as 50% of particles of 5 μm aerodynamic diameter (Sass-Kortsak *et al.*, 1993).

The performance of the nylon cyclone, the horizontal elutriator and an aluminium cyclone for measuring wood dust were compared directly in an environmentally controlled chamber at various levels of humidity. Higher levels (by about 25%) were consistently measured with the aluminium cyclone than with the elutriator, with which higher levels (by about 40%) were measured than with the nylon cyclone (Sass-Kortsak *et al.*, 1993). It has been suggested that the nylon cyclone does not accurately separate respirable and nonrespirable wood dust particles because of static charge effects with dry wood dust. The Mine Safety Appliances (MSA) respirable dust cassette, which is similar to the standard 37-mm plastic cassette but contains an aluminium inner capsule that is weighed with the filter, is reportedly about twice as efficient for measuring respirable wood dust as the standard plastic cassette (Moore *et al.*, 1990).

Samplers have been developed to measure exposure to the 'inspirable (or inhalable) particulate mass' fraction, which includes large particulates that may deposit and cause adverse effects on the upper airways. As defined by the American Conference of Governmental Industrial Hygienists (Phalen *et al.*, 1986), these samplers must maintain a sampling efficiency ≥ 50% for particles up to 100 μm aerodynamic diameter. A similar definition was proposed by the International Standards Organization (Vincent & Mark, 1990). The development, evaluation and use of specific samplers for the inspirable particulate mass, including wood dust, have been reported (Mark & Vincent, 1986; Hinds, 1988; Vaughan *et al.*, 1990; Vincent & Mark, 1990; Pisaniello *et al.*, 1991).

An early method for characterizing exposure to wood dust is determination of the number, rather than the mass, of particles in a given volume of air. The konimeter has been used extensively to measure respirable dust of 0.5–5.0 μm by drawing random, small volume, short duration spot ('grab') samples through a small orifice where airborne particles impinge on a glass slide coated with adhesive. The particles trapped on the slide are counted electronically or visually with a microscope. The measurements in grab samples are not, however, comparable to longer duration, time-weighted average concentrations (Holliday *et al.*, 1986).

(c) Particle size distribution

When the distribution of particle sizes in an air sample is to be assessed, other methods must be used. The commonest involves a multi-stage cascade impactor (e.g. the Anderson impactor), which separates particles by mass. The impactor consists of a series of perforated plates through which air is drawn at a constant rate. The dynamics of air flow through the holes (which are of different sizes at each stage) result in trapping of particles with a known range of aerodynamic diameters. The dust collected at each stage can be weighed, and a particle size (mass) distribution can be calculated. Results are reported in various ways, for example as percentage of total mass of dust collected at each stage or as mass median aerodynamic diameter (Whitehead *et al.*, 1981a; Carlin *et al.*, 1981; Holliday *et al.*, 1986; Clayton Environmental Consultants, 1988; Pisaniello *et al.*, 1991).

Holliday *et al.* (1986) reported the analysis of wood dust samples by optical microscopy and classification of particles by equivalent circular diameters calculated from their projected areas by an image analysing computer. The result is a particle size frequency distribution, rather than particle mass distribution.

(d) Other characteristics of wood dust

Other characteristics of airborne wood dust are occasionally reported. For example, the irregular shapes of wood dust particles are sometimes recorded in photomicrographs (Holliday *et al.*, 1986) or examined by scanning electron microscopy (McCammon *et al.*, 1985). Particle density (specific gravity) has occasionally been reported (Andersen *et al.*, 1977).

The chemical substances that are natural components, additives or adsorbed contaminants are sometimes extracted with water or organic solvents and characterized (see below). Although there is no standard procedure for measuring the extractable fraction of wood dust, the possible role of these substances in the adverse health effects of wood dust has been the subject of considerable research and speculation.

1.3.2 Chemical analysis of wood constituents

A survey of several methods for the chemical analysis of wood constituents has been published (Fengel & Wegener, 1989). In general, organic matter (extractives), inorganic matter (ash) and the main cell wall components, polysaccharides and lignin, are determined. It is important to select a sample for analysis that is representative of the wood species. Standardized sampling procedures have been published: e.g. TAPPI Standard T 257 cm-85 (Technical Association of the Pulp and Paper Industry, 1985a). Before chemical analysis, wood must be milled (particle size, 0.05–0.40 mm) to achieve complete penetration of reagents (Fengel & Wegener, 1989).

(a) Extractives

As no modern standard method for the extraction of wood exists, every research group has its own strategy for isolating and identifying chemical constituents of wood. The differences in reported data may thus be due to differences in wood composition or the use of different analytical methods. Conventional methods for investigating compounds present in wood involve either steam distillation or extraction with organic solvents in a soxhlet extractor (Mayer *et al.*, 1969, 1971; Nabeta *et al.*, 1987; Christensen *et al.*, 1988; Kubel *et al.*, 1988; Charrier *et al.*, 1992; Weissmann *et al.*, 1992). Table 7 shows the results of soxhlet extraction of four common wood species with a series of organic solvents of increasing polarity (Weissmann *et al.*, 1992). Supercritical fluid extraction has also been used to isolate these compounds (Torul & Olcay, 1984; Demirbaş, 1991), providing much higher yields of some compounds than those achieved with conventional soxhlet extraction. The thermal stability of wood components is not well characterized, and both soxhlet and supercritical fluid extraction may cause molecular changes, such as decomposition and dimerization (Fengel & Wegener, 1989).

Table 7. Yields (%) of successive extractions of four common wood species

Extraction solvents	European spruce	Scots pine		European beech	European oak	
		Sapwood	Heartwood		Sapwood	Heartwood
Non-polar fractions						
Petroleum ether	0.6	2.2	8.6	0.2	0.15	0.15
Diethyl ether	0.2	0.06	0.8	0.1	0.15	0.35
Polar fractions						
Acetone:water 9:1	0.7	0.3	0.7	1.6	3.6	5.8
Ethanol:water 8:2	0.3	0.4	0.4	1.2	0.9	1.8
Totals	1.8	3.0	10.5	3.1	4.8	8.1

From Weissmann *et al.* (1992)

Groups of non-polar and polar substances resulting from extraction with solvents of increasing polarity can be purified further by chromatographic techniques, such as normal and especially reverse-phase high-performance liquid chromatography (Zinkel, 1983; Suckling *et al.*, 1990; Charrier *et al.*, 1992) and thin-layer chromatography (Nabeta *et al.*, 1987; Kubel *et al.*, 1988). Individual substances are identified by infrared and one- or two-dimensional nuclear magnetic resonance spectroscopy and gas chromatography followed by mass spectroscopy (Mayer *et al.*, 1971; Nabeta *et al.*, 1987; Fengel & Wegener, 1989).

(b) Inorganic compounds in ash

The inorganic part of wood is analysed as ash after incineration of the organic wood material at 600–850 °C (Fengel & Wegener, 1989). Detailed methods for ash determination are described in TAPPI Standard T 211 om-85 (Technical Association of the Pulp and Paper Industry, 1985b) and ASTM Standard D 1102-56 (American Society for Testing and Materials, 1965). Particular ash constituents can be identified by methods such as energy dispersive X-ray analysis coupled with scanning or transmission electron microscopy, atomic absorption or emission spectroscopy and neutron activation analysis (Fengel & Wegener, 1989).

(c) Polysaccharides

Polyoses, the second group of cell wall polysaccharides, differ from cellulose in their solubility in alkali. Only some polyoses are soluble in water. Some can be extracted directly, and others require removal of lignin before extraction, usually by treating pre-extracted wood with an acidified solution of sodium chlorite (pH 4) at 70–80 °C for 3–4 h. A standard procedure for the isolation and determination of polyoses is successive extraction of chlorite holocellulose with 5 and 24% potassium hydroxide. The insoluble residue represents cellulose.

A general procedure for isolating and determining polysaccharides consists of hydrolysis with concentrated acids and subsequent dilution steps to achieve secondary hydrolysis. Sugars can be identified and quantified after hydrolysis by various chromatographic methods, including thin-layer and high-performance liquid chromatography, gas chromatography partly combined with mass spectroscopy and ion-exchange chromatography via sugar borate complexes.

(d) Lignin

All methods for the isolation of lignin have the disadvantage that they fundamentally change the native structure of lignin or release only parts of it relatively unchanged. All lignin samples obtained by acid hydrolysis are changed with regard to structure and properties, predominantly by condensation reactions. These preparations are therefore not suitable for investigating structures but can be used for estimating lignin content. The commonest method for obtaining relatively unchanged lignin is Björkman's procedure of vibratory milling and subsequent extraction of lignin with aqueous dioxane (Björkman, 1956). In one modification of this method, ultrasound is applied during the extraction step to reduce the isolation time (Wegener & Fengel, 1978).

1.4 Exposure to wood dust and other agents in the workplace

1.4.1 General influences on occupational exposure to wood dust

Woodworking operations such as sawing, milling and sanding both shatter lignified wood cells and break out whole cells and groups of cells (chips). The more cell shattering that occurs, the finer the dust particles that are produced. For example, sawing and milling are mixed cell shattering and chip forming processes, whereas sanding is almost exclusively cell shattering. Since wood cells usually measure about 1 mm, airborne dust concentrations depend primarily on the extent of cell shattering rather than on the size or extent of chip formation (Holliday *et al.*, 1986; Hinds, 1988).

In general, the harder the wood, the more tightly bound are the cells; therefore, more shattering occurs with hardwoods, resulting in more dust. Similarly, the cells in dry wood are less plastic and more likely to be shattered, leading to dust formation. While the moisture content of different species of trees varies, it is also influenced by the freshness (greenness) of the wood. Drying and some other processing of wood, such as sawing and machining, may change the chemical composition of wood dust. For example, some of the low-relative-molecular-mass extractives, such as monoterpenes (see section 1.1.4(*b*)(i)), may be volatilized. Terpenes evaporate from coniferous wood when it warms up during sawing of logs and edging of boards, and concentrations of 100–550 mg/m^3 have been measured in these operations in Swedish sawmills (Hedenstierna *et al.*, 1983).

The orientation of the point of operation relative to the wood surface and grain also influences the generation of dust. Woodworking operations performed parallel to the natural grain of the wood are less likely to shatter cells than processes performed perpendicular to the grain. The volume of wood dust generated also depends on how the process is carried out. For example, machine sanding normally generates more dust than manual sanding.

Woodworking machines have increased greatly in efficiency since the industrial revolution, and the increased speed of production has resulted in the generation of more dust. The increased efficiency may also result in exposure to finer wood dust particles than in the past, because smoother surfaces can be produced and because saws and bits may retain their sharpness for longer. The introduction of engineering controls in some industries in some parts of the world, especially since the 1950s, has, however, reduced the exposure of workers considerably. Various measures can be taken to control exposure. A simple, effective measure is to remove the worker from the point of operation by placing controls away from the process or by providing an enclosed booth. These measures are not infrequently taken in sawmills, primarily for safety reasons. Another option is to enclose the operation or to provide local exhaust ventilation. For example, Hampl and Johnston (1985) reported on a ventilation system for horizontal belt sanding that can significantly reduce wood dust emissions, and the American Conference of Governmental Industrial Hygienists (1992) has developed design guides for local ventilation in specific woodworking operations. Unfortunately, engineering controls, even if properly maintained, are not always effective, and the dust generated by hand-held power tools, particularly sanders, is much more difficult to control.

A number of characteristics of the workplace may also affect the level of wood dust, e.g. the age, density and types of woodworking machinery and the regulatory environment. Regulations with regard to exposure to wood dust and the enforcement of those regulations may vary between countries or even between industries in the same country. Small workplaces are difficult to regulate and, for various reasons, may have fewer engineering controls in place. The use of engineering controls and occupational health regulations have also changed over time.

The quality of and methods used for cleaning are important, because wood dust that has settled on the floor, equipment and other surfaces may become resuspended. In particular, the use of compressed air hoses to clean off surfaces results in high airborne concentrations of wood dust, while wet cleaning methods and use of vacuum systems may result in little or no exposure to dust. Respirators can be used to reduce exposure, and, because of the size of wood dust particles, even simple paper masks can be relatively effective if properly fitted and used. Woodworking operations conducted outdoors or in semi-enclosed buildings may involve lower exposures because of natural ventilation, but higher exposures could result from wind and the lack of local exhaust ventilation and other engineering controls.

1.4.2 Extent of exposure to wood dust

The number of workers exposed to wood dust worldwide has not been estimated in the literature; however, estimates are available for some western countries. The National Occupational Exposure Survey, carried out in 1981–83 in the United States, estimated that about 600 000 workers were exposed to wood dust. The largest numbers of exposed workers were employed in the building trades and the lumber/wood product industries. Forestry workers, e.g. lumberjacks using chain saws, were not considered to be exposed in this survey (United States National Institute for Occupational Safety and Health, 1990). The United States produced 24% of all sawn wood in the world in 1990 (FAO, 1992). According to a Finnish survey, about 70 000 workers were exposed to wood dust in logging or in production of sawn wood, wood products and pulp (Anttila *et al.*, 1992); of these, about 12 900 were estimated to have been exposed routinely to more than 1 mg/m^3 of wood dust and 3800 routinely to more than 5 mg/m^3 (Welling & Kallas, 1991). Some occupations, such as construction carpenters, were considered to have experienced only occasional exposure to wood dust, and they were not included in the Finnish estimates.

[Country-specific estimates and production statistics allow a crude estimate to be made of the number of the workers exposed worldwide. Assuming that the technical level (workforce demand) and the internal structure of the industries that involve exposure to wood dust are approximately the same as in the reference countries, the United States and Finland, the Working Group estimated that the number of workers occupationally exposed to wood dust worldwide is at least two million and probably much higher.]

The industrial hygienic measurements reviewed in sections 1.4.3–1.4.7 and Tables 8–12 include both personal and area sampling. The results probably represent daily average exposures reasonably well because the sampling time required is normally several hours. Many measurements are made for compliance testing, and workers who have moderate or high potential for exposure tend to be monitored more frequently than others. The results, therefore, are considered to be representative for the specific jobs and operations monitored but are not necessarily representative of exposures throughout industry or for all time periods, job categories or sites.

1.4.3 Exposure during sawmilling

Measured concentrations of wood dust in the air of sawmills and planing mills are presented in Table 8. The levels vary widely, ranging from 0.1 to over 100 mg/m^3; the mean values are more frequently below than above 1 mg/m^3. In the largest study of sawmills and planing mills in the United States, 33% of the measured concentrations exceeded 1 mg/m^3 and 8% exceeded 5 mg/m^3 (Clayton Environmental Consultants, 1988). The highest exposure often occurs in the vicinity of chippers, saws and planers, but other operations, such as cleaning, grading and maintenance, may sometimes be dusty.

The results presented in Table 8 are not directly comparable across studies and countries. For example, the low concentrations reported from Canada (Teschke *et al.*, 1994) are partially due to representative sampling. This strategy tends to provide lower results than selective sampling from sites and operations involving high exposure, which is the procedure used in many other studies. The method of measurement and the use of the geometric rather than the arithmetic mean in reporting may also affect the results (see section 1.3.1).

Most measurements reported in the literature are from the 1980s. There are no comprehensive data available to indicate any clear changes over time in the level of wood dust in sawmills or planing mills.

The species of wood processed in sawmills vary. In the Canadian study (Teschke *et al.*, 1994), coniferous (soft) wood, such as hemlock and fir, was processed. Coniferous species (pine and spruce) are also the main raw materials in Finnish sawmills (Welling & Kallas, 1991). Locally and in countries where coniferous trees are rare, deciduous trees may be the main wood used in sawmills. For example, a sawmill in West Virginia, United States, processed white oak,

Table 8. Concentrations of wood dust in sawmills and planer mills

Industry and operation (country)	No. of measurements	Mean[a] (mg/m³)	Range (mg/m³)	Year	Reference
Sawmills (Canada)	18		0.3–6.1	1985	Holliday *et al.* (1986)
Sawmills (Canada)	78	0.2[b]	ND–6	1982–1989	Vedal *et al.* (1986)
Sawmilling (Canada)	191[c]				Teschke *et al.* (1994)
Sawmills		0.1[d]			
Yard		0.1[d]			
Maintenance		0.2[d]			
Powerhouse		0.2[d]			
Log boom, kiln, other		0.1[d]			
Sawmills (USA)	55	2.6	0.7–10.6	1981–82	Morey (1982)
Sawmills and planing mills (USA)	193	0.7[d]	0.10–410	1987–88	Clayton Environmental Consultants (1988)
Sawmills (Finland)				1980–85	Welling & Kallas (1991)
Sawing	18	1.6	0.1–4.9		
Stacking	3	0.2	0.1–0.3		
Trimming	33	2.8	0.1–28.0		
Packaging	14	1.4	0.23–3.3		
Chipper, hogger	7	1.8	0.6–3.0		
Sawmills (Denmark)	85	0.5[e]	0.5–0.6[f]	NR	Vinzents & Laursen (1993)
Sawmills (Germany)	6	2.7[b]	0.2–50	NR	Scheidt *et al.* (1989)
Planer mill (Canada)	NR	0.2[d]		1989	Teschke *et al.* (1994)
Planer mills (Finland)				1980–85	
Sawing	8	7.8	0.6–35.2		
Planing	11	2.0	0.1–8.4		

ND, not detectable; NR, not reported
[a] Arithmetic mean unless otherwise specified; time-weighted average personal and/or area samples
[b] Median
[c] Including planer mill
[d] Geometric mean
[e] Mean of geometric means

red oak, poplar, soft maple, basswood and cherry (Morey, P., 1982, cited in United States National Institute for Occupational Safety and Health, 1987).

Sawmill workers may be exposed to chemical agents other than wood dust. Chlorophenols have been used widely in sawmills since the 1940s to prevent staining of freshly cut timber. The chlorophenols used most commonly were pentachlorophenol, tetrachlorophenols and trichlorophenols, which were usually applied to wood as water-soluble salts by dipping or spraying. Although the levels of chlorophenols reported in the air are usually below 0.1 mg/m^3, heavy exposure may occur through the skin when boards are handled manually immediately after treatment (Kalliokoski & Kauppinen, 1990). Some impurities of chlorophenols—chlorinated phenoxyphenols and polychlorinated dibenzofurans—have also been identified in the sawdust of trimming-grading plants (Levin *et al.*, 1976). Because of concern about the health effects of chlorophenates and their possible contamination with polychlorinated dibenzo-*para*-dioxins (IARC, 1987c), fungicides and other substitutes have been introduced. In Canada and the United States, a mixture of didecyldimethyl ammonium chloride and 3-iodo-2-propynyl butyl carbamate is used (Teschke *et al.*, 1995). Exposure to fungicides may occur if the boards are handled while still wet during grading, sorting and other operations. Many woods, especially those that have been kiln dried, may not need to be treated with fungicides, and some species, such as red cedar, are not susceptible to sapstain fungus.

The numbers of natural fungi and bacteria in wood increase during storage and drying and become suspended in air when wood is processed or handled. For example, the average concentration measured with an Andersen sampler in sawing departments and stacking sites of Finnish sawmills was about 14 000 colony-forming units (cfu)/m^3 of mesophilic bacteria, 130 cfu/m^3 of actinomycetes, 660 cfu/m^3 of xerophilic fungi, 6500 cfu/m^3 of mesophilic fungi and 3000 cfu/m^3 of thermotolerant fungi (Kotimaa, 1990).

In specialized mills, wood may be further treated with preservatives, fire retardants or chemicals that protect the surface from mechanical wear or weathering. For example, railroad ties, pilings, fence posts, telephone poles and other wood expected to be in contact with soil or water may be treated with creosote oils (see IARC, 1985b), pentachlorophenol solutions or salts containing copper, chromium (see IARC, 1990) and arsenic (see IARC, 1987a). Stains and colourants may also be used, and paint may be applied to seal the ends of boards or to add company marks.

1.4.4 Exposure during the manufacture of plywood and other boards

Concentrations of wood dust in the air of plywood, particle-board and other wood-based panel mills are presented in Table 9. The mean levels in plywood mills are often close to 1 mg/m^3. In a study in the United States, 27% of the measured values exceeded 1 mg/m^3 in hardwood veneer/plywood mills and 11% in softwood veneer/plywood mills (Clayton Environmental Consultants, 1988). The heaviest exposures usually occur in finishing departments where plywood is sawn and sanded. Some operations, such as drying, assembly and hot pressing, entail hardly any exposure to wood dust.

Table 9. Concentrations of wood dust in plywood, particle-board and related industries

Industry and operation (country)	No. of measurements	Mean[a] (mg/m^3)	Range (mg/m^3)	Year	Reference
Plywood mills (USA)				1978	Whitehead *et al.* (1981a)
Edge sawing, sanding, plywood machining	12	1.7	0.7–3.2		
Veneer lathe, clipper, dryer, dry veneer handling, gluing and pressing	13	0.4	0.1–0.7		
Hardwood veneer and plywood mills (USA)	48	0.8[b]	0.1–21	1987–88	Clayton Environmental Consultants (1988)
Softwood veneer and plywood mills (USA)	56	0.6[b]	< 0.1–6.4	1987–88	Clayton Environmental Consultants (1988)
Veneer and plywood mill (Canada)	7		0.1–2.6	1985	Holliday *et al.* (1986)
Plywood mills (Finland)					
Log debarking/cutting	4	0.4	0.2–0.7	1975–84	Kauppinen (1986)
Peeling	2	NR	0.2–0.3	1975–84	
Sawing of veneers	3	1.6	0.6–3.0	1965–74	
Sawing of veneers	4	1.3	1.1–1.5	1975–84	
Sawing of plywood	6	3.3	0.5–12	1965–74	
Sawing of plywood	11	3.7	0.3–19	1975–84	
Sanding of plywood	5	3.0	0.3–6.4	1965–74	
Sanding of plywood	21	3.8	0.8–22	1975–84	
Chipping in finishing department	11	2.6	0.7–7.1	1975–84	
Finishing department	18	0.7	0.3–2.4	1975–84	
Plywood mills (Finland)				1980–85	Welling & Kallas (1991)
Sawing	24	2.1	0.4–5.0		
Sorting, cleaning, glue mixing, hogger	4	11.1	7.1–15.0		
Particle-board mills (Finland)					Kauppinen & Niemelä (1985)
Hogging	3	11	0.1–29	1975–84	
Chipping	3	1.1	0.7–1.7	1975–84	
Drying of chips	2	NR	24–29	1965–74	
Blending	3	5.3	1.0–8.0	1965–74	
Blending	3	0.8	0.6–0.9	1975–84	
Forming	9	13	4.0–26	1965–74	

Table 9 (contd)

Industry and operation (country)	No. of measurements	Mean[a] (mg/m^3)	Range (mg/m^3)	Year	Reference
Particle-board mills (Finland) (contd)					Kauppinen & Niemelä (1985)
Forming	4	0.4	< 0.1–0.5	1975–84	
Hot pressing	6	4.1	1.0–6.1	1965–74	
Hot pressing	5	0.8	< 0.1–2.1	1975–83	
Sawing	4	14	10–20	1965–74	
Sawing	9	1.1	< 0.1–2.3	1975–84	
Reconstituted-board mills (USA)	112	0.7[b]	0.1–205	1987–88	Clayton Environmental Consultants (1988)
Reconstituted-board mill (Canada)	5		1.5–5.1	1985	Holliday *et al.* (1986)
Process hard-board mills (USA)	116	0.6[b]	< 0.1–45	1987–88	Clayton Environmental Consultants (1988)
Fibre-board mill (Finland)					Welling & Kallas (1991)
Piling of boards	2	2.6	1.8–3.3	1980–85	
Sawing of boards	2	3.2	1.8–4.6	1980–85	

NR, not reported
[a] Arithmetic mean unless otherwise specified; time-weighted average personal and/or area samples
[b] Geometric mean

The levels of wood dust in various reconstituted-board (particle-board, fibre-board, hardboard, strand-board) mills exceeded 1 mg/m^3 in 22% of measurements in a large study in the United States (Clayton Environmental Consultants, 1988); however, much higher concentrations have been reported, e.g. in forming and sawing of particle-board, especially before the 1980s (Kauppinen & Niemelä, 1985).

Some data on changes in exposure levels over time are presented in the Table. The level of exposure during sawing and sanding in Finnish plywood mills did not change significantly in two consecutive 10-year periods (Kauppinen, 1986). A substantial decrease in exposure since the mid-1970s has been seen, however, in dusty operations in particle-board mills (Kauppinen & Niemelä, 1985).

Phenol–formaldehyde resin adhesives are widely used to produce softwood plywood for use under severe service conditions, such as for construction and boat building. Urea–formaldehyde resin adhesives are used extensively in producing hardwood plywood for furniture and interior panelling and can be fortified with melamine resin to increase their strength. Before the introduction of formaldehyde-based resins in the 1940s, soya bean and blood-albumin adhesives were used, and cold pressing of panels was common. These operations are still used, but are increasingly rare.

Other agents to which some plywood workers may be exposed include formaldehyde (see monograph, p. 217) and phenol (see IARC, 1989b) emitted from glues, pesticides, heating emissions from coniferous veneers, solvents from coating materials and engine exhaust from forklift trucks. Pesticides that have been used in plywood glues include lindane (see IARC, 1987d), aldrin (see IARC, 1974), heptachlor (see IARC, 1991), chloronaphthalenes, chlorophenols and tributyltin oxide. The mean level of formaldehyde in most operations is now below 1 ppm (1.23 mg/m^3), and exposure to phenol is usually well below that concentration. Most pesticides mixed in glues are only slightly volatile and are not detectable in workroom air; the exception is chloronaphthalenes, which are more volatile. Exposure to pesticides may also occur through the skin. The levels of solvents during painting and other surface treatment of plywood are 1–50 ppm. Levels of terpenes in plywood mills are not detectable (< 1.5 ppm) in most operations, and the levels were only 1–6 ppm during debarking of pine logs and peeling, drying and sorting of pine veneers, in spite of the obvious presence of a blue haze during processing of pine (Kauppinen, 1986).

Formation of polycyclic aromatic hydrocarbons due to heating during sawing and sanding of plywood could not be detected in measurements carried out in a Finnish plywood mill; however, these compounds may occur in glueing and finishing departments of plywood mills, from exhausts of forklift trucks (Kauppinen, 1986).

Exposures in reconstituted-board mills are similar to those in plywood mills. Formaldehyde-based resins, and especially urea–formaldehyde resin (Kauppinen & Niemelä, 1985), are commonly used in glueing particle-board and other wood-based panels, and the level of formaldehyde in particle-board mills may exceed 1 ppm (1.23 mg/m^3). Urea–formaldehyde resins release formaldehyde during curing more readily than phenol–formaldehyde resins; however, improvements in resin formulation have reduced exposures (Holliday *et al.*, 1986). Exposure may also occur to pesticides, such as heptachlor, and solvents in surface coatings

(Kauppinen & Niemelä, 1985). Workers in the area of stockpiles of untreated wood chips or conveyors used to transport the chips may be exposed to moulds, bacteria and fungi (Cohn *et al.*, 1984).

1.4.5 Exposure during wooden furniture manufacture and cabinet-making

Table 10 summarizes the levels of wood dust in the wooden furniture industry, including cabinet-making. The reported mean levels are higher than in sawmilling and wood-based panel manufacture: a concentration of 1 mg/m^3 was exceeded in 41% of measurements in household furniture manufacture, in 22% in office furniture manufacture and in 52% in kitchen cabinet manufacture in the United States (Clayton Environmental Consultants, 1988). The mean levels shown in Table 10 are frequently between 1 and 10 mg/m^3. The highest exposures occur in wood machining jobs, such as sanding, and in cabinet-making. Wood is usually machined in separate departments of large furniture plants, but some dusty jobs, such as sanding between applications of varnish layers (e.g. French polishing), may be done in surface coating departments (Welling & Kallas, 1991).

Both hardwood and softwood are commonly used in the manufacture of furniture. The proportions of different species of wood used depends on many factors, such as the country, product, plant and period considered. For example, in the British plants surveyed in 1983 (Jones & Smith, 1986), beech, ash, elm, mahogany, walnut, veneered particle-board and medium density fibre-board were used. In the Finnish furniture industry in 1986, mainly pine and birch were used, but spruce, oak, mahogany, teak and other wood species were employed to some extent (Welling & Kallas, 1991). Case reports and epidemiological studies provide some additional information on the species of wood used in the past in furniture factories of different countries (see section 2).

The mean level of wood dust in seven British furniture factories decreased from 7.8 mg/m^3 (138 samples) in 1976–77 to 4.2 mg/m^3 (209 samples) in 1983, probably due mostly to improvements in local exhaust ventilation of machines (Jones & Smith, 1986).

Other agents than wood dust to which workers in furniture and cabinet-making may be exposed include formaldehyde and solvents from varnishes, paints and glues. In spray-varnishing and -painting and in sanding of surface-coated furniture, workers may also be exposed to nonvolatile components of surface coatings, such as pigments and resins. The level of formaldehyde in the air of surface coating departments of furniture plants varies from 0.1 to over 5 ppm (0.12–> 6.15 mg/m^3), often averaging close to 1 ppm (1.23 mg/m^3). Workers who machine wood may occasionally be exposed to formaldehyde if, for example, formaldehyde-based glues are used in veneering and the hot press is situated close to wood processing machines. In addition, formaldehyde may be released from reconstituted panels during machining (Sass-Kortsak *et al.*, 1986) or may be bound in wood dust aerosol (Stumpf *et al.*, 1986).

Glueing, staining and varnishing are generally done at a distance from woodworking operations, however, so that machine operators and cabinet-makers, who are usually heavily

Table 10. Concentrations of wood dust during furniture and cabinet-making

Industry and operation (country)	No. of measurements	Mean[a] (mg/m^3)	Range (mg/m^3)	Year	Reference
Furniture manufacture (United Kingdom)				1973	Hounam & Williams (1974)
Turning	2	8.6	4.6–12.5		
Band sawing	6	4.3	1.0–7.3		
Routing	6	4.1	1.8–8.6		
Assembly	9	5.5	2.1–9.8		
Planing	9	5.0	1.8–10.9		
Sanding	9	7.2	2.0–22.6		
Spindle moulding	8	5.1	1.5–8.4		
Furniture manufacture (United Kingdom)				1983	Jones & Smith (1986)
Conversion	43	2.3	1.0–4.8		
Component making	106	3.4	0.3–53		
Assembly	60	7	0.5–27		
Furniture manufacture (Denmark)				1974–75	Andersen *et al.* (1977)
Drilling, planing, sawing	27	5.2			
Machine and hand sanding	41	14.3			
Furniture manufacture (USA)				1978	Whitehead *et al.* (1981a)
Rough mill (softwood)	5	0.6	0.2–1.1		
Rough mill (hardwood)	7	0.8	0.2–2.6		
Assembly (softwood)	2	2.8	2.5–3.1		
Assembly (hardwood)	3	1.5	1.1–2.1		
Lathe, planer, router (hardwood)	9	1.8	0.2–6.3		
Lathe, planer, router (softwood)	9	1.6	0.3–4.3		
Sanding (hardwood)	12	4.5	1.4–11.4		
Sanding (softwood)	13	3.2	0.6–14.3		
Manufacture of household furniture (Canada)				1985	Holliday *et al.* (1986)
Processing of hardwood	11		0.3–5.2		
Processing of particle-board	6		0.5–6.8		
Processing of softwood, particle-board	5		1.7–15.6		
Manufacture of office furniture (Canada)				1985	Holliday *et al.* (1986)
Processing of hardwood	7		0.5–1.7		
Processing of particle-board	9		0.4–5.6		

Table 10 (contd)

Industry and operation (country)	No. of measurements	Mean[a] (mg/m³)	Range (mg/m³)	Year	Reference
Manufacture of household furniture (USA)	112	1.3[b]	0.2–240	1987–88	Clayton Environmental Consultants (1988)
Manufacture of office furniture (USA)	23	0.8[b]	0.2–3.8	1987–88	Clayton Environmental Consultants (1988)
Furniture factories (Germany)				NR	Scheidt *et al.* (1989)
Routing, planing	10	6.0[c]	3–59		
Sanding	8	2.8[c]	1.2–9.1		
Sanding (manual)	8	6.1[c]	2.7–17		
Sawing	19	2.9[c]	0.4–123		
Furniture manufacture (Australia)				1989–90	Pisaniello *et al.* (1991)
Wood machinists	99	3.2	0.4–24		
Cabinet-makers	57	5.2	0.4–19		
Chair framemakers	15	3.5	2.0–7		
Manufacture of furniture and fixtures (Finland)				1980–85	Welling & Kallas (1991)
Boring	3	8.7	0.9–22		
Lathing	6	14	1.8–64		
Machine sanding	47	18	0.6–320		
Planing	9	0.8	0.1–2.5		
Routing	10	6.4	0.7–15		
Sanding between varnishing operations	17	16	0.4–81		
Sawing	44	6.8	0.3–73		
Spindle moulding	5	12	0.6–45		
Trimming	2	0.8	0.3–1.3		
Hand sanding	8	20	0.5–60		
Furniture factories (Sweden)	28	2.0	0.3–5.1	NR	Wilhelmsson & Drettner (1984)
Furniture manufacture (Denmark)	396	1.1[d]	1.1–1.2[e]	NR	Vinzents & Laursen (1993)
Cabinet-making (Czechoslovakia)			1961–62		Kubiš (1963)
Belt sander	10	24	3.6–65		
Cabinet-making shop (United Kingdom)	71	8.1		NR	Al Zuhair *et al.* (1981)

Table 10 (contd)

Industry and operation (country)	No. of measurements	Mean[a] (mg/m³)	Range (mg/m³)	Year	Reference
Cabinet-making (Canada)		NR	1984		Sass-Kortsak *et al.* (1986)
Assembly	19	1.9			
Laminating, graphics, glueing	3	1.1			
Sanding	7	2.9			
Sawing	12	1.7			
Miscellaneous work	7	1.2			
Manufacture of kitchen cabinets (Canada)			1985		Holliday *et al.* (1986)
From hardwood	12	0.3–5.1			
From particle-board	5	0.7–3.7			
Manufacture of kitchen cabinets (USA)	42	1.6[b]	0.3–13	1987–88	Clayton Environmental Consultants (1988)

NR, not reported
[a] Arithmetic mean unless otherwise specified; time-weighted average personal and/or area sample
[b] Geometric mean
[c] Median
[d] Mean of geometric means
[e] Range of geometric means

exposed to wood dust, are not exposed regularly to other chemicals: The mean exposure of cabinet-makers to formaldehyde was usually low (< 0.1 ppm [< 0.23 mg/m^3]) in a Canadian study (Sass-Kortsak *et al.*, 1986). The mean level of solvents in finishing departments was about 20% of the national exposure limit of a mixture in Danish measurements in the early 1990s (Vinzents & Laursen, 1993) and about 40% in Finnish measurements in 1975–84 (Priha *et al.*, 1986). The solvents used are typically mixtures of several chemicals, such as aliphatic hydrocarbons (solvent naphtha, white spirit [see IARC, 1989c]), aromatic hydrocarbons (toluene [see IARC, 1989d], xylene [see IARC, 1989e]; less often benzene [see IARC, 1987e] and styrene [see IARC, 1994a]), esters, alcohols, ketones and glycol ethers (Partanen *et al.*, 1993). The constituents of solvent mixtures can vary, e.g. by country, period and facility. Pigments and other agents that may be used in furniture factories have been listed elsewhere (IARC, 1981).

1.4.6 Exposure during the manufacture of other wood products

The concentrations of wood dust measured during the manufacture of wooden doors, windows, prefabricated buildings, boats and other wood products are presented in Table 11. Measurements made during unspecified woodworking, which may be related to production of furniture or other wood products, are also included in the Table. The mean concentrations are similar to those in furniture manufacture because largely similar machining operations are used. The highest exposures occur in wood machining operations, where the mean levels are usually 1–10 mg/m^3.

No studies on changes over time in the levels of wood dust in these industries were available to the Working Group, but in some countries levels may have declined during the last few decades, as in the furniture industry (see section 1.4.5). The main reason is use of local exhaust systems for woodworking machines. Comparative measurements made in woodworking shops in Germany with the exhaust on and off indicate that the concentration of wood dust is very high when the exhaust system is out of operation (see Table 11; Wolf *et al.*, 1986).

As in the furniture industry, many species of softwoods and hardwoods are used. For example, in the study in Germany mentioned above, mainly oak and beech were used but many workers had also been exposed to pine, spruce and other species (Wolf *et al.*, 1986). Coniferous wood species are frequently used in the manufacture of window frames, doors and prefabricated buildings, and about 90% of all wood used in this way in Finland in 1986 was pine or spruce (Welling & Kallas, 1991).

Other agents that occur in workroom air depend on the products and processing methods used; they may include surface coatings (solvents, resins, pigments), glues (formaldehyde, phenol, epoxy compounds, polyurethanes) and engine exhaust, and the levels may be comparable to those found in the furniture industry (see section 1.4.5). Wood is usually coated and treated away from dust-generating operations, because dust may interfere with the application of chemicals; however, solvents, formaldehyde and other vapours may spread to areas where wood processing operations are being performed, and exposure may also occur through dermal contact from handling treated wood, through the release of chemicals into the air when treated wood is heated during wood processing operations, or through inhalation of dust from treated wood.

Table 11. Concentrations of wood dust in other wood product industries

Industry and operation (country)	No. of measurements	Mean[a] (mg/m³)	Range (mg/m³)	Year	Reference
Woodworking shops (Germany)				NR	Wolf *et al.* (1986)
Sawing with exhaust	91	[5.9]	0.2–47		
Sawing without exhaust	22	[34.4]	1.5–184		
Moulding with exhaust	64	[5.6]	0.1–60		
Moulding without exhaust	12	[17.3]	1.2–113		
Sanding with exhaust	69	[8.3]	0.3–55		
Sanding without exhaust	13	[56.7]	3.7–500		
Assembly with exhaust	6	[5.2]	1.0–11		
Assembly without exhaust	19	[9.3]	0.7–40		
Woodworking shops (Germany)				1987–88	Albracht *et al.* (1989)
Sanding	84	3.6[b]			
Sawing	88	2.4[b]			
Moulding	38	1.0[b]			
Planing	27	1.1[b]			
All-round woodworkers	42	2.0[b]			
Woodworking shops (Germany)				NR	Scheidt *et al.* (1989)
Sawing, routing, sanding	6	5.1[b]	2.9–6.6		
Woodworking (USA)				1987–88	Clayton Environmental Consultants (1988)
Saw operators	191	0.8[c]	< 0.1–240		
Sander operators	85	1.2[c]	0.1–41		
Milling machine operators	111	1.2[c]	0.1–250		
Woodworking machine shops (United Kingdom)				NR	Hamill *et al.* (1991)
Hard- and softwood processing	7		0.5–5.1		
Softwood processing	37		0.3–55		
Hard- and softwood processing	51		0.5–33		
Woodworking factories (Denmark)	153	0.9[d]	0.4–1.3[e]	NR	Vinzents & Laursen (1993)
Joinery workshops (France)	6	22	2.4–73	NR	IARC (1981)

Table 11 (contd)

Industry and operation (country)	No. of measurements	Mean[a] (mg/m³)	Range (mg/m³)	Year	Reference
Joinery shops (Sweden)				NR	Nygren *et al.* (1992)
Circular sawing	13	0.5[c]			
Sanding	15	1.2[c]			
Cutting	20	0.3[c]			
Manufacture of doors and windows (Finland)				1980–85	Welling & Kallas (1991)
Machine sanding	5	3.4	1.4–6.7		
Packaging	2	1.5	1.4–1.5		
Sawing	6	2.0	1.2–3.3		
Spindle moulding	2	1.4	1.3–1.4		
Manufacture of doors and windows (Denmark)	118	0.6[d]	0.6–0.8[e]	NR	Vinzents & Laursen (1993)
Manufacture of prefabricated buildings (Canada)	8		0.4–2.5	1985	Holliday *et al.* (1986)
Manufacture of prefabricated houses (Finland)				1980–85	Welling & Kallas (1991)
Sawing	5	1.8	0.6–4.6		
Spindle moulding	2	2.9	0.6–5.1		
Manufacture of signs and plaques (USA)				1983	McCawley, M. (1983; cited in United States National Institute for Occupational Safety and Health, 1987)
Router, sander	18	3.2	1.0–8.1		
Wood component fabrication (USA)				1975	Kominsky & Anstadt (1976)
Router/groover operator	5	21.8	1.4–51.0		
Saw operator (total particulate)	19	68.8	0.7–688		

Table 11 (contd)

Industry and operation (country)	No. of measurements	Mean[a] (mg/m³)	Range (mg/m³)	Year	Reference
Boat building (USA)				1983	Crandall, M.S. & Hartle, R.W. (1984; cited in United States National Institute for Occupational Safety and Health, 1987)
Carpenters in assembly	27	2.4	0.3–16.2		
Manufacture and repair of wooden boats (Finland)	4	1.2	0.8–1.8	1980–85	Welling & Kallas (1991)

NR, not reported
[a] Arithmetic mean unless otherwise specified; time-weighted average personal and/or area samples
[b] Median
[c] Geometric mean
[d] Mean of geometric means
[e] Range of geometric means

Potential exposure to pesticides is high in the building of wooden boats because the wood must be protected from decay and marine borers (Jagels, 1985). Manufacture of windows, garden furniture, balcony decks, railroad ties, piers and other wooden structures for outdoor use may entail exposure to wood preservatives, such as chlorophenols, creosote, chromated copper arsenate and ammoniacal copper arsenate. The concentration of arsenic around various types of joinery machines was 0.5–3.1 μg/m^3 in six Swedish joinery shops using wood impregnated with copper–chromium–arsenic salt . The concentration of chromium was 0.4–2.3 μg/m^3 and that of copper was 0.4–1.9 μg/m^3. No hexavalent chromium was found (Nygren *et al.*, 1992). Exposure to low levels of arsenic has also been reported in factories where wood is impregnated with arsenic-containing preservatives (Rosenberg *et al.*, 1980). Insulation materials used in the manufacture of prefabricated houses often contain man-made mineral fibre products, such as glasswool and stonewool (Rockwool©) (see IARC, 1988). A number of other chemicals may be used as additives, including inorganic salts as fire retardants and chlorophenates as preservatives (Suchsland & Woodson, 1986).

1.4.7 Exposures in other wood-related occupations

Table 12 summarizes the concentrations of wood dust in some other wood-related occupations and operations, including flooring and parquet laying, pattern and model making, wood handling in pulp mills and teaching art and vocational skills.

The level of exposure in wooden model making in the automotive industry and in metal foundries averaged about 1 mg/m^3 in a study in the United States (McCammon *et al.*, 1985). Model makers use a wide variety of woodworking machines and hand tools in preparing models. Prototypes are made of softwoods, such as pine, bass, jelutong, plywood lavan and mahogany. Mahogany has been used for die models, but cativo wood impregnated with phenol–formaldehyde resin is now commonly used. Paints, sealers and lacquers that release various solvents are used to coat models. Model-making may also involve use of adhesive systems, such as white glues and epoxy resins, and plastics like carvable putties, fibre glass and poly-foams. Model-making also requires the use of glues that contain epoxy compounds and amines. The highest solvent concentration measured in the United States was 10% of the exposure limit of the mixture; no formaldehyde or amines were detected in air (McCammon *et al.*, 1985).

Some building trades entail exposure to wood dust. Sanding of parquet before varnishing is a dusty operation, which is usually carried out by specialized workers. Varnishes applied to parquets and wooden floors often contain formaldehyde-based resins and organic solvents, and the level of exposure to formaldehyde during varnishing may be over 1 ppm (1.23 mg/m^3). Construction carpenters use handsaws and circular saws both indoors and outdoors; however, since no measurements of exposure to wood dust were available to the Working Group, the mean level is probably low. Construction carpenters may also be exposed occasionally to other agents in the wide variety of activities carried out at construction sites. Most tasks on a construction site are performed by specialized workers, and it is unlikely that carpenters would be involved in e.g. painting, but different trades often work side-by-side, resulting in potential cross-exposure to e.g. other dusts and insulation materials. In addition, small construction

Table 12. Concentrations of wood dust in other wood-related occupations

Industry and operation (country)	No. of measurements	Mean[a] (mg/m^3)	Range (mg/m^3)	Year	Reference
Wooden model making (USA)				1980	Enright, J.C. (1980; cited in United States National Institute for Occupational Safety and Health, 1987)
Research and safety model shop	10	0.9	0.2–3.4		
Wood mill	10	4.7	1.2–10.2		
Pattern making (Canada)	5		1.0–2.6	1985	Holliday *et al.* (1986)
Automotive wood model shop (USA)				NR	McCammon *et al.* (1985)
Model makers/hardwood	12	0.6	0.2–0.3		
Model makers/soft- and hardwood	23	0.8	0.2–8.3		
Model makers/softwood	4	0.3	0.2–0.5		
Multi-axis machine operators	4	0.5	0.2–1.0		
Sweepers	5	1.6	0.1–6.1		
Shapers	7	2.7	0.3–13.9		
Wood mill (general)	10	0.3	0.05–0.5		
Parquet sanding (Germany)	5	6.6[b]		1987–88	Albracht *et al.* (1989)
Flooring/hard- and softwood (Canada)	7		0.3–1.7	1985	Holliday *et al.* (1986)
Parquet sanding (Germany)	2	9.3	4.4–14	NR	Scheidt *et al.* (1989)
Pulp/paper mill (USA)				1987–88	Clayton Environmental Consultants (1988)
Chipping, debarking, screening, loading	19	0.3[c]	< 0.1–18		
Art school (USA)				1976	Levy, B.S.B. (1976; cited in United States National Institute for Occupational Safety and Health, 1987)
Sawing, sanding, planing	8	6.0	0.9–24.2		
University art department (USA)	4	3.5	1.6–5.7	1980	Lucas & Salisbury (1992)

[a] Arithmetic mean unless otherwise specified; time-weighted average personal and/or area samples
[b] Median
[c] Geometric mean

companies and those using non-union labour may not make clear distinctions between the responsibilities of different trades.

Pulp making and some papermaking processes start with retrieval of logs from storage, debarking and then chipping, and workers handling wood are exposed to wood dust, although the level of exposure is usually below 1 mg/m^3 (Table 12). High levels of fungal spores and bacteria have been found occasionally at wood and chip handling sites of pulp and paper mills (Kotimaa, 1990). Teachers and other personnel working in vocational and art schools may also have occupational exposure to wood dust (Table 12). Exposure may be high, owing to poor ventilation, but it is generally not continuous.

Forestry workers are a large occupational group who process and handle wood regularly. Lumberjacks have cut trees for centuries, first with axes and handsaws and, since about 1950, with chain saws. No measurements were available of their level of exposure to wood dust, but it is probably lower than those usually found in wood industries. Other exposures of forestry workers include engine exhaust (see IARC, 1989f) from chain saws and forest vehicles, chain oils and gasoline (see IARC, 1989g) used as fuel for chain saws.

1.4.8 Particle size distribution of wood dust in workroom air

Exposures to wood dust can be characterized not only by the mass (or number of particles) per unit volume of air but also by the distribution of particle sizes. Wood dust particles are typically irregular in shape and have rough surfaces, as observed by scanning electron microscopy; however, no differences in morphological pattern have been noted among samples from different operations (Liu *et al.*, 1985).

Several investigators have reported particle size distributions for wood dust in workplace air in various industries. Representative studies are summarized in Tables 13 and 14. In most studies, the major portion of the wood dust mass is contributed by particles larger than 10 μm in aerodynamic diameter (Whitehead *et al.*, 1981a; Darcy, 1984; Lehmann & Fröhlich, 1987, 1988; Hinds, 1988; Pisaniello *et al.*, 1991). This is attributable, in part, to the fact that larger particles are also heavier. Holliday *et al.* (1986) used an optical microscopy method (see section 1.3.1) to count particles in various size ranges and found that 61–65% (as calculated by the United States National Institute for Occupational Safety and Health, 1987) of the particles measured 1–5 μm.

Some investigators have reported that the particle size distribution varies substantially according to woodworking operation, sanding producing more small particles and sawing producing more large particles (Hounam & Williams, 1974; Darcy, 1984; Liu *et al.*, 1985). Other investigators, however, have found no consistent differences (Holliday *et al.*, 1986; Lehmann & Fröhlich, 1988; Pisaniello *et al.*, 1991).

There is also some evidence that processing (especially sanding) of hardwoods can generate a higher percentage of small particulates than processing of softwoods, although again the evidence is by no means consistent and other studies have shown no differences. Whitehead *et al.* (1981a) suggested that processing of hardwoods may lead to higher concentrations of respirable dust than processing of softwoods, on the basis of a comparison of 15 samples taken

Table 13. Particle size distribution of hardwood dust (%)

Wood, operation	Total dust (mg/m³)	Stage[a]								
		0	1	2	3	4	5	6	7	Back-up filter
Oak, hand sanding	6.9	72.6	9.6	5.1	3.3	2.3	1.7	1.7	1.5	2.2
Oak, machine sanding	2.7	65.0	12.2	3.9	4.2	3.0	3.4	3.0	2.1	3.3
Oak, sanding (hand portable machine)	2.7	47.2	14.6	7.2	9.1	7.0	4.8	2.6	2.3	5.2
Oak and beech, sawing and machine sanding	5.4	44.4	21.9	7.0	7.2	2.9	2.4	1.1	2.4	10.7
Particle-board and beech, sawing and planing	9.4	65.1	15.9	6.1	8.2	2.8	0.9	0.5	0.5	0.0
Ash, hand sanding	1.9	49.5	16.7	14.3	10.1	4.3	2.2	1.2	0.0	1.7
Beech, sawing	4.1	62.7	12.7	9.5	3.5	2.9	2.8	2.4	1.9	1.6

From Lehmann & Fröhlich (1988)

[a] Stage 0, > 9.0 mm; stage 1, 5.8–9.0; stage 2, 4.7–5.8; stage 3, 3.3–4.7; stage 4, 2.1–3.3; stage 5, 1.1–2.1; stage 6, 0.65–1.1; stage 7, 0.43–0.65

Table 14. Wood dust sizes measured in the workplace in various studies

Study description	Equipment/operation	Sampling device	Mass median aerodynamic diameter (mm)	Reference
Cabinet-making (Czechoslovakia), 1 plant, 1961–62; area samples/total dust	Belt sander	NR	Up to 95%, < 5 Most, 2–3	Kubiš (1963)
Furniture (England), 5 plants, 1973; personal samples/total dust	Band sawing, turning Planing Routing, moulding Sanding Assembly	Four-stage cascade centripeter	11.5 9.2 10.0 8.4 7.6 (< 25%, < 5)	Hounam & Williams (1974)
Furniture (Denmark), 8 plants, 1974–75; personal samples/total dust	Sanding, drilling, planing, sawing	NR	33% (mass), < 5 41% (mass), 6–10 11% (mass), 11–15 15% (mass), > 16	Andersen *et al.* (1977)
Wooden component fabrication (USA), 1 plant, 1975; personal samples	Saw operator, router/ groover operator	Six-stage cascade impactor	> 10	Kominsky & Anstadt (1976)
Wooden products (USA), 2 plants, 1976; personal samples	Shake mill (western red cedar)	Cyclone unit	39%, < 10 23%, 10–20 38%, > 20	Edwards *et al.* (1978)
	New planer mill (Douglas fir/hemlock)	Cyclone unit	47%, < 10 25%, 10–20 28%, > 20	
Plywood/furniture (USA), 12 plants, 1978; area samples/total dust	Veneer lathe/clipper, dryer, dry veneer handling, edge sawing/ sanding, machining, assembly, milling, sanding	Six-stage cascade impactor	[1.3] mg/m^3 < 5.5[a] [3.3] mg/m^3 < 14.1[a]	Whitehead *et al.* (1981a)

Table 14 contd)

Study description	Equipment/operation	Sampling device	Mass median aerodynamic diameter (mm)	Reference
Furniture (England), 2 plants, 1981; personal samples/total dust	Sawmill Assembly Machine floor Cabinet shop	Seven-stage cascade impactor	17.3 18.0 9.3 12.5	Al Zuhair *et al.* (1981)
Wooden model making (USA), 3 shops, 1981–82; personal samples/total dust	Model maker, sweeper, shaper operator, plastic shop worker, multi-axis machine operator	Nine-stage cascade impactor	7.7 (range, 5.2–10); 18–61% respirable dust[b]	McCammon *et al.* (1985)
Furniture (England), 7 plants, 1983; personal samples/total dust	Machine sanding, hand sanding, sawing, other cutting	Impactor	9 (54% (mass), 4–10)	Jones & Smith (1986)
Signs/plaques (USA), 1 shop, 1983; area samples/ total dust	Router, sander	Four-stage cascade impactor	46–60% (mass), < 3.5 30–35% (mass), 3.5–20 5–20% (mass), > 20	McCawley, M. (1983; cited in United States National Institute for Occupational Safety and Health, 1987)
Woodworking (Finland), 1 shop, 1983; personal samples/total dust	Unloading wood, sawing, other machines, planing	Optical microscopy	97.8%, < 5	Lindroos (1983)
Plywood (Finland), 6 mills, 1984; personal and area samples/total dust	Sawing Finishing General workroom	MSA cyclone	40% respirable dust 29% respirable dust 65% respirable dust	Kauppinen *et al.* (1984)
Particle-board (USA), 1 plant, 1986; area samples/ total dust	Sanding	Six-stage cascade impactor	8.26	Stumpf *et al.* (1986)
Various industries (Canada), 23 plants, 1985; personal samples/total dust	Sawing Sanding Planing/routing/shaping	Optical microscopy	62%, 1–5 61%, 1–5 65%, 1–5	Holliday *et al.* (1986)

Table 14 contd)

Study description	Equipment/operation	Sampling device	Mass median aerodynamic diameter (mm)	Reference
Various industries (Germany), 17 factories, 2 training shops, 1983–85; personal and area samples	Sanding, sawing, routing/ planing	Anderson impactor	44.4–72.6%, > 9 9.6–21.9%, 5.8–9 3.9–14.3%, 4.7–5.8 3.3–10.1%, 3.3–4.7 2.3–7.0%, 2.1–3.3 0.9–4.8%, 1.1–2.1 0.5–3.0%, 0.7–1.1 0–2.4%, 0.4–0.7 0–10.7%, 0–0.4	Lehmann & Fröhlich (1987)
Various industries (Hong Kong), 3 factories; personal samples	Sawmill, sanding (furniture factory), mixing (mosquito-coil factory)	Scanning electron microscopy	9–12.8%, > 10 18–26.1%, 5–10 61.7–73%, 0–5	Liu *et al.* (1985)
Furniture (Australia), 15 factories, 1989; personal samples	Sanding Sawing Mixed woodworking	IOM/7-hole; cascade impactor	16–19 17–22 15–23	Pisaniello *et al.* (1991)

NR, not reported; MSA, Mine Safety Appliances Co. (Pittsburgh, PA); IOM, Institute of Occupational Medicine

[a] Gravimetric concentrations are given, rather than percentages. Of the 15 samples reported, only two contained dust of a mass median aerodynamic diameter < 5.5 µm at concentrations ≥ 1 mg/m^3, and only three contained dust < 14.1 µm at > 2 mg/m^3.

[b] Scanning electron microscopy indicated that length-to-width ratios were 2.3:1 and 1.9:1 in two air samples collected with a 0.5-in [1.3-cm] stainless-steel cyclone.

during furniture and plywood manufacture. Darcy (1982), however, found that the distribution of particle sizes from sanding pine and oak were very similar (see distribution curves reproduced by Hinds, 1988). Pisaniello *et al.* (1991) reported only a very slight difference in the average mass median aerodynamic diameter of dust from hardwood (18.7 μm; geometric standard deviation (GSD), 2.0) and from softwood/reconstituted wood (19.6 μm; GSD, 2.1).

1.5 Regulations and guidelines

Several countries have set standards or guidelines for occupational exposures to wood dust, with 8-h time-weighted average (TWA) exposure limits ranging from 1 to 10 mg/m^3 (United States National Institute for Occupational Safety and Health, 1987, 1992). In the regulations of some countries, a particular class of wood dust is named (e.g. 'hardwood' and 'softwood'). For example, in the United Kingdom, the long-term exposure limit (8-h TWA) for hardwood and softwood is 5 mg/m^3; for hardwood, there is a notation that the substance can cause respiratory sensitization, and the limit for softwood is noted for intended change (United Kingdom Health and Safety Executive, 1992). In Canada, the limits are 1 mg/m^3 for hardwood and 5 mg/m^3 for softwood (United States National Institute for Occupational Safety and Health, 1987). In Germany, dusts of oak and beech have been classified as human carcinogens (group III A1) since 1985, and other wood species are suspected of having carcinogenic potential (group III B). The technical exposure limit for total wood dust was set at 2 mg/m^3 for all industrial plants in 1993. The limit of 5 mg/m^3 set up for old industrial plants in 1987 will no longer be allowed, with a few exceptions, by 31 December 1995 (Deutsche Forschungsgemeinschaft, 1993). In Sweden also, wood dust is considered potentially carcinogenic (United States Occupational Safety and Health Administration, 1987).

In other countries, wood dust is regulated under more general categories of particulate matter. In Hungary and Poland, for example, dust of vegetable and animal origin is regulated; dust containing various percentages of free silica are regulated in Poland (United States Occupational Safety and Health Administration, 1987). Standards for organic dusts are used for wood dust in Finland (8-h threshold limit value [TLV], 5 mg/m^3; maximum for 15 min, 10 mg/m^3) (Työministeriö, 1993). Switzerland has no specific standards for wood dust but controls 'total dust' and 'fine dust' (United States National Institute for Occupational Safety and Health, 1987).

The American Conference of Governmental Industrial Hygienists (1993) recommended the following TLVs: 1 mg/m^3 for an 8-h TWA for wood dust (certain hardwoods such as beech and oak); and 5 mg/m^3 TWA and 10 mg/m^3 for the short-term exposure limit to softwoods, with the notation that the substance has been identified elsewhere as a suspected human carcinogen. Similar exposure limits have been adopted by several other countries (e.g. Australia, New Zealand and Norway) as regulations or guidelines (United States National Institute for Occupational Safety and Health, 1987). 'Particulates not otherwise regulated' are covered in the United States (United States Occupational Safety and Health Administration, 1993).