1. Exposure Data

1.1 Chemical and physical data

1.1.1 *Nomenclature and general description*

Man-made vitreous fibre (MMVF) is a generic name used to describe an inorganic fibrous material manufactured primarily from glass, rock, minerals, slag and processed inorganic oxides. The MMVFs produced are non-crystalline (glassy, vitreous, amorphous). Other names for MMVFs include manufactured vitreous fibres, man-made mineral fibres (MMMF), machine-made mineral fibres and synthetic vitreous fibres. Continuous glass filament is sometimes also referred to as 'glass textile fibre'.

The term 'mineral wool' has been used in the USA to describe only rock (stone) wool and slag wool. In Europe, 'mineral wool' also includes glass wool. In this monograph, the terms rock (stone) wool, slag wool and glass wool are used rather than mineral wool, whenever possible.

Man-made vitreous fibres are manufactured by a variety of processes based on the attenuation of a thin stream of molten inorganic oxides at high temperatures. All commercially important MMVFs are silica-based and contain various amounts of other inorganic oxides. The non-silica components typically include, but are not limited to, oxides of alkaline earths, alkalis, aluminium, boron, iron and zirconium. These additional oxides may be constituents of the raw materials used to make the fibres, or they may be added to enhance the manufacturing process or the product performance.

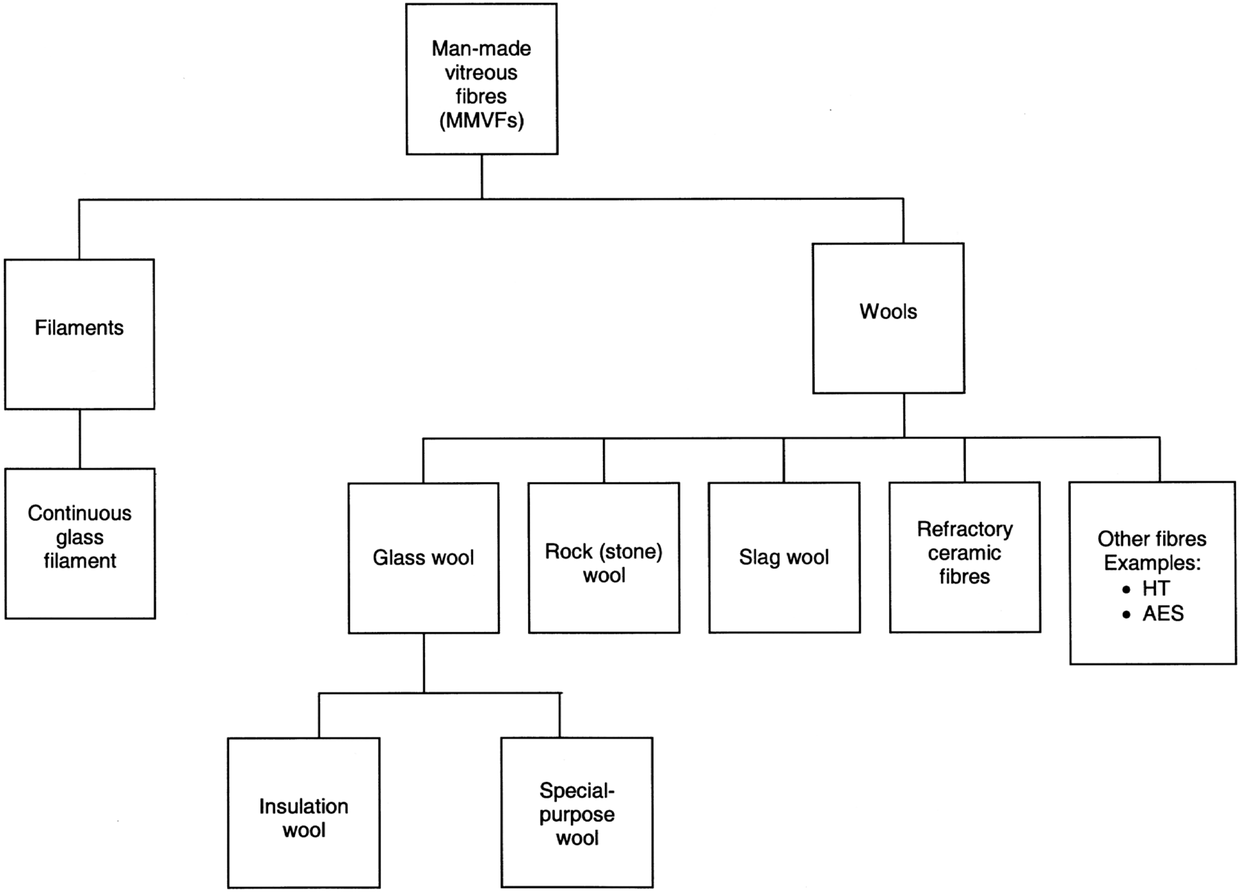
Depending on the process of fibre formation, MMVFs are produced either as wool, which is a mass of tangled, discontinuous fibres of variable lengths and diameters, or as filaments, which are continuous fibres (of indeterminate length) with diameters having ranges that are more uniform and typically thicker than those of wool.

(*a*) *Categorization*

The previous *IARC Monographs* on man-made mineral fibres (IARC, 1988) grouped fibres into five categories based loosely on raw materials, production process and/or product application. These categories were: glass filament, glass wool, rock wool, slag wool and ceramic fibres.

To reflect developments in the industry, the categories have been expanded and modified somewhat in this monograph, as depicted in Figure 1. The present monograph

Figure 1. Categories of MMVFs



Within each of these categories, there are commercial products representing a range of compositions and durabilities.
AES, alkaline earth silicate wools; HT, high-alumina, low-silica wools

includes only vitreous fibres, whereas the 1988 monograph also included some crystalline ceramic fibres (e.g. silicon carbide) used in high-temperature applications. In this monograph, the MMVFs evaluated in the ceramic fibre category are wool-type fibres known as refractory ceramic fibres.

Certain characteristics of MMVFs such as their respirability and biopersistence in the lung have been the focus of increased attention and research in recent years, and a number of new fibres with reduced biopersistence have been developed. These fibre characteristics are discussed in detail in section 4.1, and the regulatory categorization systems adopted by the European Union and by several other countries, based on biopersistence and respirability, are described in section 1.5. The development of the newer fibres is recognized in Figure 1 under the category ‘other fibres’. Examples of more biosoluble fibres include the alkaline earth silicate wools and the high-alumina, low-silica wools. Other newly developed fibres may be less biosoluble and more biopersistent.

Finally, the generic names of several categories of MMVFs have been updated in the current monograph (i.e. glass filament → continuous glass filament; glasswool → glass wool; rockwool → rock (stone) wool; slagwool → slag wool; ceramic fibres → refractory ceramic fibres (see also General Remarks on Man-made Vitreous Fibres).

1.1.2 *Chemical and physical properties*

(*a*) *Chemical properties*

The MMVFs have a broad variety of chemical compositions as shown in Table 1. Within each traditional category of MMVF, the composition of the fibres may vary substantially. Several factors account for the compositional variability of MMVFs:

End-use: The end-use of each product requires fibres to have specific chemical and physical characteristics. For example, ‘continuous glass filament’ includes eight distinctly different fibre types. Each type has its own formulation with a narrow range of variability. The formulations differ considerably from one another because each type is designed for a specific set of performance criteria, such as high strength, high electrical resistivity or resistance to attack by various chemical agents. Similarly, the grades of refractory ceramic fibres designed for high-temperature (1000–1460 °C) end-uses may have a high alumina and zirconia content (Maxim *et al.*, 1999a; EIPPCB, 2000; Mast *et al.*, 2000a).

Manufacturing requirements: Variations in manufacturing processes and in the availability of raw materials are responsible for much of the compositional variation in glass, rock (stone) and slag wools.

Biopersistence considerations: MMVFs have historically been made with a range of compositions and associated durabilities. Since it was recognized that fibre biopersistence affects the potential effects on respiratory health and that fibre chemistry is an important determinant of biopersistence, the industry has introduced some new,

Table 1. Typical chemical compositional ranges for classes of MMVFs expressed as oxide mass percentage (for the major constituents found in most commercially important MMVFs)

	Continuous glass filament[a]	Glass wool[b,c]		Rock (stone) wool[d]	Slag wool[b,c]	Refractory ceramic fibres[c]	Alkaline earth silicate wool[e]	High-alumina, low-silica wool[f]
		Insulation wool	Special-purpose fibre					
SiO_2	52–75	55–70	54–69	43–50	38–52	47–54	50–82	33–43
Al_2O_3	0–30	0–7	3–15	6–15	5–16	35–51	< 2	18–24
CaO	0–25	5–13	0–21	10–25	20–43	< 1		
MgO	0–10	0–5	0–4.5	6–16	4–14	< 1		
MgO + CaO	0–35	5–18	0–25.5	16–41	24–57		18–43	23–33
BaO	0–1	0–3	0–5.5					
ZnO	0–5		0–4.5					
Na_2O		13–18	0–16	1–3.5	0–1	< 1		
K_2O		0–2.5	0–15	0.5–2	0.3–2	< 1		
$Na_2O + K_2O$	0–21	12–20.5			0.3–3		< 1	1–10
B_2O_3	0–24	0–12	4–11	< 1	< 1		< 1	
Fe_2O_3[g]	0–5	0–5	0–0.4		0–5	0–1	< 1	
FeO				3–8				3–9
TiO_2	0–12	0–0.5	0–8	0.5–3.5	0.3–1	0–2		0.5–3
ZrO_2	0–18		0–4			0–17	0–6	
$Al_2O_3 + TiO_2 + ZrO_2$							< 6	
P_2O_5				< 1	0–0.5			
F_2	0–5	0–1.5	0–2					

Table 1 (contd)

	Continuous glass filament[a]	Glass wool[b,c]		Rock (stone) wool[d]	Slag wool[b,c]	Refractory ceramic fibres[c]	Alkaline earth silicate wool[e]	High-alumina, low-silica wool[f]
		Insulation wool	Special-purpose fibre					
S					0–2			
SO_3		0–0.5						
Li_2O	0–1.5	0–0.5						

[a] Hartman *et al*. (1996)

[b] EIPPCB (2000) (includes the new less biopersistent fibre-types)

[c] TIMA (1993)

[d] Guldberg *et al*. (2000)

[e] ECFIA & RCFC (2001)

[f] Guldberg *et al*. (2002) (HT fibre; CAS No. 287922-11-6)

[g] Total iron expressed as Fe_2O_3

less biopersistent fibre compositions. To accomplish this, the industry has extended the traditional compositional ranges of MMVFs in several ways:

— by increasing the content of alkali oxides and borate in glass wools;

— by substituting alumina for silica or alkaline earth oxides for alumina in rock wools; and

— by developing high-temperature-resistant compositions based on the alkaline earth silicate (AES) wools as an alternative to the aluminosilicate compositions of refractory ceramic fibres, in some applications.

The raw materials that have been commonly used to make MMVFs are listed in Table 2. The sources for the raw materials include the following (TIMA, 1993):

Mined: materials mined or quarried from the earth that have received only minimal physical processing to ensure the required particle size and reasonable chemical homogeneity.

Processed: mined materials that have received minimal chemical processing such as thermal treatment to remove water or carbonate.

Recycled: materials that are by-products of the manufacture of MMVFs or other manufacturing processes.

Manufactured: relatively pure manufactured chemical compounds.

(i) *Continuous glass filament*

Most of the continuous glass filament produced worldwide has an E-glass composition (Table 3), developed solely for electrical applications and more than 98% of all continuous glass filament currently produced is of this type (EIPCCB, 2000; APFE, 2001). E-glass is a calcium-aluminosilicate glass, in which the alkali oxides of sodium and potassium are maintained at low concentrations (< 2 weight %) to achieve acceptable electrical properties. Boron oxide is often a major additive, but in recent years, alternative formulations of E-glass without boron oxide have been developed to reduce emissions of boron compounds into the air during production and to lower the cost of raw material. These boron-free formulations are used in applications other than printed circuit boards or aerospace materials (Hartman *et al.*, 1996).

Other types of glass are also produced as continuous filament. These are used in applications that require specific properties such as high mechanical strength, increased temperature resistance, improved resistance to corrosion, resistance to alkali in cement or low dielectric properties (see Table 3). C-glass is resistant to acids and is used in composites that come into contact with mineral acids and as a reinforcement material in bituminous roofing sheet. AR-glass is used for cement reinforcement and differs from other glasses in that it contains zirconium oxide, which provides resistance to corrosion by alkalis. S-glass is a high-strength glass developed in the 1960s for applications such as rocket motor cases. S-glass is difficult and costly to make and is therefore limited to highly technological uses (Loewenstein, 1993; Hartman *et al.*, 1996; APFE, 2001).

Table 2. Raw materials commonly used in the manufacture of MMVFs

Raw material	Desired element	Source	Continuous glass filament	Glass wool		Rock (stone) wool	Slag wool	Refractory ceramic fibre	AES wool	High-alumina, low-silica wool
				Insulation wool	Special-purpose fibre					
Anorthosite	Al, Si	Mined								x
Basalt	Si, Ca, Mg, Fe	Mined				x	x			x
Bauxite	Al	Mined					x			x
Colemanite	B	Mined	x		x					
Dolomite	Ca, Mg	Mined	x	x	x	x	x		x	x
Fluorspar	F	Mined	x		x					
Kaolin clay	Al	Mined	x	x	x			x		
Limestone	Ca	Mined	x	x	x	x	x			x
Nepheline syenite	Al	Mined		x		x	x			
Silica sand	Si	Mined	x	x	x	x	x	x	x	x
Ulexite	B	Mined		x						
Wollastonite	Ca, Si	Mined			x				x	
Zircon sand	Zr, Si	Mined			x			x	x	
Briquettes (artificial stones)	Si, Al, Ca, Mg	Processed								x
Burned dolomite	Ca, Mg	Processed	x	x	x				x	
Granite	Si, Al	Processed				x	x			x
Alu-dross	Al	Recycled								x
Blast furnace slag	Si, Al, Ca, Mg	Recycled				x	x			x
Converter slag	Fe, Ca	Recycled								x
Cullet[a]	Si, Ca, Mg, Na, B	Recycled		x						
Ladle slag	Al, Fe, Ca	Recycled								x
Alumina	Al	Manufactured		x	x			x		x
Borax (5 H_2O)	B	Manufactured		x						
Magnesia	Mg	Manufactured							x	
Magnesite	Mg	Manufactured	x		x					

Table 2 (contd)

Raw material	Desired element	Source	Continuous glass filament	Glass wool		Rock (stone) wool	Slag wool	Refractory ceramic fibre	AES wool	High-alumina, low-silica wool
				Insulation wool	Special-purpose fibre					
Manganese dioxide	Oxidizing power	Manufactured		x						
Sodium nitrate	Oxidizing power	Manufactured		x						
Sodium carbonate	Na	Manufactured		x						
Sodium sulfate	Oxidizing power	Manufactured	x	x		x	x			
Zirconia	Zr	Manufactured	x		x			x		

From TIMA (1993)

AES, alkaline earth silicate

[a] Cullet (broken or waste glass) includes purchased recycled cullet and cullet recycled from the same manufacturing plant.

Table 3. Typical chemical compositional ranges of representative continuous glass filament expressed as oxide (wt%)

	E-glass (high electrical resistivity)	ECR-glass (high electrical resistivity, corrosion resistant)	C-glass (acid resistant)	D-glass (low dielectric constant)	R-glass (high strength)	AR-glass (alkali resistant)	S-glass (high strength, high-temperature resistant)
SiO_2	52–56	54–62	64–68	72–75	55–65	55–75	64–66
Al_2O_3	12–16	9–15	3–5	0–1	15–30	0–5	24–25
CaO	16–25	17–25	11–15	0–1	9–25	1–10	0–0.1
MgO	0–5	0–4	2–4		3–8		9–10
BaO			0–1				
ZnO		2–5					
$Na_2O + K_2O$	0–2	0–2	7–10	0–4	0–1	11–21	0–0.2
Li_2O						0–1.5	
B_2O_3	5–10		4–6	21–24		0–8	
Fe_2O_3[a]	0–0.8	0–0.8	0–0.8	0–0.3		0–5	0–0.1
TiO_2	0–1.5	0–4				0–12	
ZrO_2						1–18	
F_2	0–1				0–0.3	0–5	

From Hartman *et al.* (1996)

[a] Total iron expressed as Fe_2O_3

(ii) *Glass wool*

In principle, many different chemical elements could be present in glass. However, in commercial glass manufacturing, the number of oxides used is limited by their cost. Almost all of the glass products manufactured have silicon dioxide, silica (SiO_2), as the single largest oxide ingredient, measured by weight or volume, in the final composition. To form a glass, a glass-forming compound, or glass former, is required. A glass former is a compound that, in its pure form, can be melted and quenched into the glassy state. In principle, the oxide glass formers can be boric oxide (B_2O_3), phosphorus pentoxide (P_2O_5) or even germanium dioxide (GeO_2), but SiO_2 is the major commercial glass former because it is readily available in a variety of inexpensive forms that can be mixed and processed into a glass (TIMA, 1993).

Although SiO_2 is the principal ingredient, it is necessary to modify the composition using other oxides, commonly referred to as either intermediate oxides or modifiers. There is no sharp distinction between the intermediates and modifiers. However, oxides such as aluminium oxide, alumina (Al_2O_3), titanium dioxide, titania (TiO_2) and zinc oxide (ZnO) are often classified as intermediates, while oxides such as magnesium oxide, magnesia (MgO), lithium oxide, lithia (Li_2O), barium oxide, baria (BaO), calcium oxide, calcia (CaO), sodium oxide, soda (Na_2O) and potassium oxide (K_2O) are usually classified as modifiers. Sometimes, the modifiers are called fluxes, while the intermediate oxides are referred to as stabilizers (TIMA, 1993).

Glasses containing a large fraction of fluxes permit reaction of the raw materials to occur at relatively low temperatures, but such glasses tend to have lower chemical resistance. As an example, a sodium silicate glass with a large fraction of sodium oxide is soluble in water and, in fact, such compositions are manufactured as soluble silicates or water-soluble glasses. The intermediate oxides help impart to a silicate glass a higher degree of chemical resistance, and they control, together with the fluxes, the viscous character of the melt, which is especially important in fiberization (TIMA, 1993).

Most glass wool has been used for a variety of insulation applications. An additional category has been used to group those glass fibres produced by flame attenuation for special applications. This category, termed ‘special-purpose fibres’ in Figure 1 and Table 1, includes, for example, fibres such as E-glass and 475-glass used for high-efficiency air filtration media, acid battery separators and certain fine-diameter glass fibres.

(iii) *Rock (stone) and slag wool*

Typical modern rock (stone) and slag wools are composed of calcium magnesium aluminium silicate glass. They are produced by melting a mixture of various slags and/or rock raw materials in a coke-fired cupola. Alternatively, they can be melted in an electric or gas-heated furnace. For rock (stone) wool, the procedure is carried out using a mixture of various natural and synthetic rock sources to yield the desired composition. In the manufacturing of both rock (stone) and slag wool, one raw material is normally the main component, and other materials are added to make up for a particular deficiency in that raw material. If, for example, the main component is too rich in acid oxides such as silica, then limestone or a slag rich in calcium oxide is added. In slag wool production, iron-ore blast-furnace slag is the primary component, while in rock (stone) wool production, basalt is usually the primary raw material. In rock (stone) and slag wool produced from materials melted in a cupola with coke as fuel, all the iron oxide is reduced to ferrous oxide (FeO). During the spinning process, a surface layer may form in which the iron is oxidized to ferric oxide (Fe_2O_3). Typically 8–15% of the iron is oxidized to ferric oxide. In an electric furnace melting basalt, up to 50% of the iron is in the form of ferric oxide which is more evenly distributed throughout the entire fibre volume than after heating in a coke-fired cupola (TIMA, 1993).

The production of slag wool in Europe began in the 1880s using slags of various types and continued until the mid-1940s. After the Second World War, most plants began using rock rather than slag as the raw material and currently most European plants continue to melt rock. In the USA, the production of rock (stone) wool dominated from about 1900 until the late 1930s when several of the rock (stone) wool plants converted to iron-ore blast-furnace slag, a waste-product in the production of pig iron because the use of slag was more economical. While the use of slags other than iron-ore blast-furnace slag was once quite widespread, this is no longer the case. Slag formed during the reduction of iron ore to pig iron is now the primary raw material used in the USA to make slag wool. It accounts for 70–90% of the weight of the raw materials that make up the slag wool. Since the mid-1970s, the slag wool industry in the USA has relied entirely on blast-furnace slag with small amounts of additives such as phosphate-smelter slag and natural materials like silica gravel, limestone, nepheline syenite and, for certain dark coloured wools, small amounts of an essentially arsenic-free copper slag. The rock (stone) wool plants use basaltic rock, limestone, clay and feldspar, together with the additives mentioned above (TIMA, 1993).

(iv) *Refractory ceramic fibres*

Refractory ceramic fibres are produced by melting a combination of alumina (Al_2O_3) and silica (SiO_2) in approximately equal proportions or by melting kaolin clay. Other oxides, such as zirconium dioxide (ZrO_2), boric oxide (B_2O_3), titanium oxide (TiO_2) and chrome oxide (Cr_2O_3) are sometimes added to alter the properties of the resulting fibres (TIMA, 1993). For example, the chemical composition is one of the factors that determine the maximum feasible end-use temperature. As for all MMVFs, the fibre length, diameter and bulk density — controllable to some degree by the manufacturing method and chemical composition — also affect key physical properties of the refractory ceramic fibres, e.g. the thermal conductivity (Everest Consulting Associates, 1996).

The basic composition of refractory ceramic fibres has not changed appreciably since their initial formulation in the 1940s (Environmental Resources Management, 1995), but modifications to the composition such as raising the content of alumina and the addition of zirconium dioxide and other materials create fibres that tolerate higher maximum end-use temperatures.

(v) *Newly developed fibres*

In recent years, the industry has developed newer fibres that have similar properties to older products, but are more biosoluble. Some examples of these newly developed fibres are the alkaline earth silicate (AES) wools and high-alumina, low-silica wools. Producers of refractory ceramic fibres and other MMVFs have developed new fibre compositions designed to withstand high end-use temperatures, but with significantly lower biopersistence than the older types. Although these new fibres can be produced in the same furnaces as are used to manufacture refractory ceramic fibres, their chemistry differs substantially from that of refractory ceramic fibres; they are new fibres rather than a modification or hybrid of refractory ceramic fibres. These new products, termed AES fibres, were first commercialized in 1991. They are wool-like products composed of alkaline earth oxides (calcium oxide + magnesium oxide) in the range of 18%–43% by weight, silica (SiO_2) in the range of 50%–80% by weight, and alumina + titania + zirconia < 6% by weight. Traces of other elements are also present (ECFIA–RCFC, 2001).

Another product introduced in the early 1990s is the high-alumina, low-silica stone wool (known as HT wool). The traditional raw materials for the production of rock (stone) wool are the rock types basalt or diabase (dolerite) in a mixture with the fluxing agents limestone or dolomite. Briquettes or form stones (artificial rocks) often bound together by cement can now be used instead of natural rocks. The briquettes make it possible to use raw materials that have a higher melting point than the melt temperature of 1500–1550 °C normally used and allow the inclusion of fine-grained high-melting temperature raw materials such as quartz sand, olivine sand and bauxite in the melt composition (Guldberg *et al.*, 2002).

(*b*) *Physical properties*

(i) *Fibre diameter*

The distribution of fibre diameters in MMVFs varies with the fibre type and the manufacturing process employed. Because they are amorphous (i.e. non-crystalline), MMVFs do not have cleavage planes that cause them to split lengthwise into fibres with smaller diameters. Rather, MMVFs break across the fibre, resulting in fibres which are of the same diameter as the original fibre but shorter, together with a small amount of dust (Assuncao & Corn, 1975).

Continuous glass filament is produced by a continuous process of drawing through the calibrated holes of the bushings at constant speed, thus leading to a very narrow variation in the filament diameter. In any given product, the diameter of the fibres differs little from the mean or nominal diameter. The standard deviation of the diameter in continuous filament products is typically less than 10% of the nominal diameter. Filaments are divided into 19 classes by a letter designation from B to U corresponding to a range of mean diameters as shown in Table 4. The nominal diameter of continuous glass filaments ranges from 5–25 μm. The majority of the filaments produced have a diameter of 9 μm or more, corresponding to G filaments and above (APFE, 2001). Small quantities of C filaments are produced in North America, and small quantities of B filaments are produced in Japan. Table 5 lists the fibres that have been tested in animal carcinogenicity studies.

The post-production processing of continuous glass filament does not cause any change in diameter. However, in a recent study, examination of dust from highly chopped and pulverized continuous glass filament by microscopy demonstrated the presence of small amounts of respirable dust particles, a small number of which had aspect ratios equal to or greater than 3:1. These elongated particles have been called 'shards' (APFE, 2001).

The fibre formation processes used to manufacture wools produce fibres with diameters that vary much more within a given wool product than within a continuous glass filament product. The diameters within a vitreous wool product have an approximately log-normal distribution. Nearly all wool products have average diameters of 3–10 μm. For example, in a wool product with an average fibre diameter

Table 4. Letter designations for continuous glass filaments

Size designation	Range of mean diameters (μm)
B	3.30–4.05
C	4.06–4.82
D	4.83–5.83
DE	5.84–6.85[a]
E	6.35–7.61[a]
F	7.62–8.88
G	8.89–10.15
H	10.16–11.42
J	11.43–12.69
K	12.70–13.96
L	13.97–15.23
M	15.24–16.50
N	16.51–17.77
P	17.78–19.04
Q	19.05–20.31
R	20.32–21.58
S	21.59–22.85
T	22.86–24.12
U	24.13–25.40

From ASTM (2000)

[a] Mixture of ranges

Table 5. List of fibres tested in the animal carcinogenicity studies performed after 1987 and reported in this monograph

Fibre	Reference
Fibres A, C, F, G, H	Lambré *et al.* (1998)
B-01-0.9 glass wool, B-09-0.6 glass wool, B-09-2.0 glass wool	Roller *et al.* (1996)
B-20-0.6 slag wool	Roller *et al.* (1996)
B-20-2.0 (experimental rock (stone) wool)	Davis *et al.* (1996a); Roller *et al.* (1996)
Bayer B1, B2, B3 (glass wools)	Pott *et al.* (1991)
104E glass fibre	Cullen *et al.* (2000)
JM 475	Pott (1989); Pott *et al.* (1989)
JM 753	Roller *et al.* (1996)
M-stone wool	Davis *et al.* (1996a); Roller *et al.* (1996)
R-stone wool-E3	Roller *et al.* (1996)
MMVF10, MMVF11	Hesterberg *et al.* (1993)
MMVF10a	Hesterberg *et al.* (1997, 1999); McConnell *et al.* (1999)
MMVF21 (rock (stone) wool)	Mc Connell *et al.* (1994)
MMVF22	Roller *et al.* (1996)
MMVF33	McConnell *et al.* (1999)
MMVF34 (or HT fibre or HT stone wool)	Kamstrup *et al.* (2001, 2002)
X-607 (or AES)	Hesterberg *et al.* (1998a)
RCF1, RCF2, RCF3, RCF4	Mast *et al.* (1995a)

of approximately 5 µm, the diameters of individual fibres may range from less than 1 µm to > 20 µm. In addition to fibres, some wool fibre formation processes can produce a considerable number of large, rounded particles approximately 60 µm or larger in diameter, which are termed 'shot' (TIMA, 1993).

The preparation of a bulk fibre sample for measurement by microscopy typically breaks the fibres into shorter lengths. Under these circumstances, it is not meaningful to report the number of fibres in various ranges of diameters. Instead, either the total length of fibres falling within each diameter range is measured, or fibres are sampled for measurement of their diameters in proportion to their lengths (the intercept method) (Schneider *et al*., 1983; Koenig *et al*., 1993; TIMA, 1993). The mean, geometric mean or median fibre diameter determined in this way is referred to as a 'length-weighted' (or 'accumulated length') mean, geometric mean or median diameter. Table 6 lists typical length-weighted mean fibre diameter and standard deviation and the shot content for various wool products. It is apparent from Table 6 that the average fibre diameter is a function of the manufacturing process and not an inherent property of a particular type of fibre (TIMA, 1993).

If, for a given sample, the number of fibres per diameter interval is determined, the corresponding median diameter will be smaller than the length-weighted median diameter, since thicker fibres tend to be longer. For this reason, the median diameter of

Table 6. Fibre length-weighted diameter and shot content for various wool products[a]

Product	Fibre diameter (µm)		Shot content (percentage by weight)
	Average	Standard deviation	
Glass wools	7.7	4.2	2
	5.8	4.7	0
	5.6	3.3	1
	5.3	3.2	5
	4.7	2.0	0
	4.0	2.4	1
	3.4	2.0	1
	3.3	2.7	0
	1.2	1.0	0
	0.6	0.5	0
Rock (stone) and slag wools	5.3	3.8	16
	4.5	4.1	49
	4.4	2.7	43
	4.0	2.4	24
	4.0	3.1	45
	4.0	3.1	39
	3.9	3.2	55
	3.5	3.5	51
	2.4	2.3	50
Refractory ceramic fibres	3.8	2.8	20
	2.4	2.2	43
Alkaline earth silicate wools[b]	2.2	2.5	35
	3.0	2.4	40
High-alumina, low-silica wool[c]	4.6	–	30

[a] From TIMA (1993)
[b] From ECFIA & RCFC (2001)
[c] From Knudsen *et al.* (1996)

the fibres in an airborne fibre cloud is smaller than the length-weighted median diameter of the fibres in the product from which it originates: settling and ventilation further shift the distribution towards lower diameters. For example, for nominal diameters of, say, 8 µm, the typical count median diameter for the airborne fibres could not exceed 3–5.5 µm, even at the moment of dispersion (Schneider *et al.*, 1983).

(ii) *Fibre length*

As with diameter, the fibre length varies according to the manufacturing process. Continuous glass filaments are produced by a continuous drawing process that results in extremely long fibres (typically several metres). During post-fibrization processing, however, fibres may be broken either intentionally or inadvertently. Thus, fibre lengths in continuous glass filament products are highly dependent on the nature of such processing. For example, the typical length of chopped strands is 3.0–4.5 mm, while that of chopped rovings is 2.5–3.0 cm (TIMA, 1993).

Wool fibres are manufactured as discontinuous fibres. In an analysis of the fibres found in glass wool insulation, most of them were found to be several centimetres long. The mean length of fibres in other wool products is variable, ranging from several centimetres to < 1 cm (TIMA, 1993). Fibres with lengths less than the 250 µm upper limit for respirability (Timbrell, 1965) are certainly present in most, if not all, wool products, and probably also in continuous filament products as a result of the various post-fibrization processes. There are no good methods to quantify the number of fibres of length < 250 µm within MMVF products (TIMA, 1993). Furthermore, the ability of fibres to become airborne depends strongly on the degree to which they are immobilized in the product by binder, other additives and facing, and on the way they are handled. Thus, the best way to evaluate fibre length in relation to health effects is to analyse the airborne dust generated during the manufacturing and handling of the MMVF product (see section 1.4).

(iii) *Fibre density*

Unlike fibre length and diameter, fibre density does not vary widely between MMVFs. The four traditional classes of MMVF range in density from 2.1–2.9 (Table 7). Fibre density, length and diameter are the critical properties that determine the aerodynamic behaviour of MMVFs and their respirability (see section 4.1.1).

Table 7. Density ranges for MMVFs

Fibre	Density (g/cm^3)
Continuous glass filament	2.1–2.7[a]
Glass wool	2.4–2.6[a]
Rock (stone) and slag wool	2.7–2.9[a]
Refractory ceramic fibres	2.6–2.7[a]
Alkaline earth silicate wools	2.6[b]
High-alumina, low-silica (HT) wools	2.8[c]

[a] TIMA (1993) and Hartman *et al.* (1996)
[b] ECFIA & RCFC (2001)
[c] Hesterberg *et al.* (1998b)

(iv) *Fibre coatings and binders*

During the drawing of continuous filament glass fibres, an aqueous polymer emulsion or solution is usually applied to each filament. This coating material is referred to as binder or size and serves to: protect the filaments from their own abrasion during further processing and handling, and ensure good adhesion of the glass fibre to the resin during polymer reinforcements. The quantity of binder on the filaments is typically in the range of 0.5%–1.5% by mass. The coating material applied varies depending on the end-use of the product. Typical coating components include: film formers such as polyvinyl acetate, starch, polyurethane and epoxy resins; coupling agents such as organofunctional silanes; pH modifiers such as acetic acid, hydrochloric acid and ammonium salts; and lubricants such as mineral oils and surfactants (EIPPCB, 2000).

MMVF wools may contain other types of additive. Oils and other lubricants may be added to wools during processing to reduce dust generation from the product. An organic binder may be applied to wools immediately after fibrization in order to hold the fibres together in a spongy mass. This binder is usually a phenol–formaldehyde resin in aqueous solution, which, after drying and curing, tends to concentrate at fibre junctions, but also partially coats the individual fibres. In rock (stone) and slag wools the binders account for up to 10% of the mass of the final product. Other additives applied to wools may include antistatic agents, extenders and stabilizers, and inhibitors of microorganisms (TIMA, 1993). In recent years, alternatives to phenol–formaldehyde resins such as melamine and acrylic resins have been used.

The binder content of insulation wool products is typically quite low, but for high-density products may range up to 25% by mass. In some products no binder is applied. Such binder-free products are designed either for an application in which integrity of the wool fibres is not necessary or in cases where that integrity is achieved by other means, such as encapsulation in a plastic sheath. Typically, some lubricant is sprayed on these fibres immediately after fibrization to protect them from mechanical damage during processing and subsequent use (TIMA, 1993).

(v) *Structural changes*

Man-made vitreous fibres are noncrystalline and remain vitreous when used at temperatures below 500 °C. At higher temperatures, they flow, melt or crystallize depending on their composition. High-silica and low-alkali metal oxide compositions such as refractory ceramic fibres, AES wools, and some rock (stone) wools will start to crystallize at temperatures above 900 °C. The crystalline phases produced will depend on composition and temperature. Longer exposure times are required for fibre devitrification at lower temperatures (Brown *et al.*, 1992; Laskowski *et al.*, 1994).

1.1.3 *Analysis*

(*a*) *Principle*

Dust samples are collected by drawing a measured quantity of air through a filter. For determination of the concentration of airborne dust, the collected dust is weighed. For the examination of fibres by optical microscopy, the filter is rendered transparent and mounted on a microscope slide. The numbers of fibres on a measured area of the filter are then counted visually using phase-contrast optical microscopy (PCOM) following a set of counting rules. Samples for scanning electron microscopy (SEM) are taken on filters that have a smooth surface suitable for direct examination. After sampling, part of the filter is cut out, mounted on a specimen stub and coated with a thin layer of gold (WHO, 1985) or platinum (Yamato *et al.*, 1998). For transmission electron microscopy (TEM), special preparation methods are used. Widely used methods of measurement, as described in WHO (1996), represent a consensus reached by experts from 14 countries, NIOSH (1994) and earlier versions of these methods. Since the sampler design specifications for optical microscopy and counting criteria have all been improved and standardized, the fibre concentrations assessed by the old and new methods may not be directly comparable.

(*b*) *Sampling*

The sampler is mounted on a worker in the breathing zone or placed in a fixed location where exposure is to be characterized. A range of filter diameters and filter-holder designs has been used. The most recent sampling methods (NIOSH, 1994; WHO, 1996) use a 25-mm diameter filter placed in an open-faced holder with a 50-mm electrically conductive extension cowl.

Fibres depositing inside the cowl are not considered in the NIOSH 7400 procedure, and WHO (1996) states that fibres rinsed from the cowl should be disregarded when calculating fibre concentration. Jacob *et al.* (1992) found average cowl losses of 25% (standard deviation (SD), 12%) for sampling during the installation of residential glass-fibre insulation. During manufacturing operations involving glass wool, the average loss was 27% (SD, 13%) (Jacob *et al.*, 1993). For refractory ceramic fibres, Cornett *et al.* (1989) found an average cowl deposition of 17% (SD, 12%).

Fibre mass and fibre concentration have been determined from separate samples (e.g. Schneider, 1979a) or from single samples used in turn for weighing and fibre counting (e.g. Ottery *et al.*, 1984). Fibre counting requires that the dust be uniformly distributed across the filter, and therefore open-faced filters are used. However, for proper sampling of inhalable and respirable dust, the samplers used must conform to the specifications given in international standards (CEN, 1993; ISO, 1995).

(*c*) *Gravimetric analysis*

Gravimetric analysis measures the total mass of dust in a volume of air. The collection filter is desiccated, conditioned to the relative humidity of the weighing room and weighed before sampling and together with the collected dust after sampling. The concentration of airborne particles, expressed as mg/m^3, is calculated from the sampling rate and the weight gain of the filter (Ottery *et al.*, 1984).

(*d*) *Fibre counting*

Fibre counting methods are used to determine the concentration of airborne fibres.

(i) *Counting criteria*

The filter is rendered optically transparent and the fibres present within a specified number of randomly selected areas are counted using a PCOM at a magnification of × 500. The total number of fibres on the filter is calculated to give the concentration of airborne fibres. Since the visibility of the thinnest fibres is dependent on the optical parameters of the microscope and on the refractive index of the filter medium, these parameters are also specified. The performance of the microscope in terms of visibility of thin fibres is assessed using a standard test slide. The microscopy techniques are based on those commonly used for the monitoring of asbestos.

A countable fibre, as defined by WHO (1996), is any particle that has a length > 5 μm, a length:diameter ratio larger than 3:1 and a fibre diameter < 3 μm (often referred to as WHO fibres).

A fibre as defined by the NIOSH ‘B’ rules (1994) is any particle that has a length > 5 μm, a length:width aspect ratio equal to or greater than 5:1 and a diameter < 3 μm.

Investigators in the USA typically used the NIOSH ‘A’ rule and its predecessor P&CAM (Physical & Chemical Analytical Method) 239 (Taylor, 1977) until the late 1980s. The ‘A’ rule has no upper diameter bound and the aspect ratio lower limit is 3:1. Thus, the ‘B’ rule is bound to give lower results than the ‘A’ rule because some fibres are excluded. The difference will depend on the bivariate fibre size distribution. Breysse *et al.* (1999) found that this difference can be significant. For samples of airborne glass and rock (stone) wool fibres, the ‘A’ rule gave approximately 70% higher results than the ‘B’ rule. For loose insulation wool without binder, applied by blowing, the difference was only 8%. For refractory ceramic fibres, the difference was 33%. However, Buchta *et al.* (1998) found no difference in the density of refractory ceramic fibres measured by the two counting rules.

The criteria for counting fibres that are branching or crossing or that are attached to other particles are marginally different between WHO (1996) and NIOSH (1994). Laboratories in the USA using the NIOSH ‘B’ rule counted fibre densities on average lower by 27% than European laboratories using the WHO method to count the same set of pre-mounted slides (Breysse *et al.*, 1994). Maxim *et al.* (1997) compared the NIOSH ’B’ rule with the WHO rule and found that use of the NIOSH ’B’ rules resulted in counts that were approximately 95% of those obtained using the WHO rules.

Criteria for counting fibres that are not completely within the counting field are also specified (NIOSH, 1994; WHO, 1996). Some of the previously used criteria have overestimated the number of long fibres (Schneider, 1979b).

(ii) *Fibre identification*

The workplace atmosphere may be contaminated by fibres other than MMVFs since, for example, fibres of cellulose, organic textiles and gypsum are ubiquitous. The presence of particles that fulfil the counting criteria, but are not MMVFs, has been acknowledged by several investigators. Jacob *et al.* (1993) studied the removal of pipe and ceiling insulation and, using the NIOSH 'B' rule, determined the arithmetic mean concentration of fibres to be 0.13 fibre/cm^3. Of the fibres present, 0.042 fibre/cm^3 were MMVFs (identified using morphology and polarized light microscopy (PLM)). In a study of workers in the prefabricated wooden house industry in Sweden, MMVFs constituted only about 25% of the total number of fibres in air samples (Plato *et al.*, 1995a).

Switala *et al.* (1994) measured MMVF concentrations near emission sources and used dispersion modelling, supplemented by PLM if it was not readily apparent that a fibre was an MMVF. When assessing exposure in non-industrial environments and exposure of the general public, care should be taken to discriminate between different types of fibre and better criteria for identifying MMVFs are required (Schneider *et al.*, 1996). The work of Draeger *et al.* (1998), Rödelsperger *et al.* (1998) and data quoted by Höfert and Rödelsperger (1998), indicate that the parallel edge criterion shows promise as a replacement for the chemical composition criterion used in the past as an inclusion criterion for MMVFs in addition to analysis of elemental composition.

NIOSH (1994) specifically states that it is incumbent on all laboratories to report all fibres meeting the counting criteria. For assessing exposure to asbestos, however, the method states explicitly that if serious contamination from other fibres occurs, PLM can be used to eliminate non-crystalline fibres of diameter > 1 µm. WHO (1996) provides guidance on the application of PLM for identifying many types of fibre with diameters > 1 µm, such as cellulose fibres, many synthetic organic fibres and asbestos fibres. The use of SEM with energy dispersive X-ray analysis (EDXA) can distinguish between various types of MMVF. Transmission electron microscopy with EDXA and electron diffraction is generally considered to be the most definitive method available for providing both chemical and structural information on fibres down to 0.01 µm in diameter (WHO, 1996). The VDI (1994) method for non-industrial environments is based on SEM and EDXA. The VDI method provides guidelines on how to attribute MMVFs to specific bulk MMVFs present in a building, according to a classification scheme based on the presence and relative intensity of characteristic energy peaks in the EDXA spectrum. Such fibres are termed 'product fibres'.

While some attention has been paid to the effect on fibre counts of changing from the NIOSH 'A' to the 'B' rule, much less attention has been paid to the differences caused by using various approaches to exclude non-MMVFs.

(iii) *Detection limit*

In optical microscopy, the practical limit of detection is about 0.2 µm. For conventional MMVFs, this is no great disadvantage, since they are mostly more than 1 µm in diameter. The median diameter of some airborne microfibres and other special-purpose fibres, however, can range from 0.1–0.3 µm, and therefore a substantial proportion of such fibres would not be detected using optical microscopy (Rood & Streeter, 1985). Furthermore, some of these fibre types may have a refractive index close to that of the filter medium, further increasing the difficulty in detecting them. In this case, special sample preparation methods should be used (Health and Safety Executive, 1988).

For the NIOSH 7400 method (B counting rules), the quantitative working range is 0.04–0.5 fibre/cm^3 for a 1000-L air sample. The detection limit depends on the sample volume and quantity of interfering dust, and is < 0.01 fibre/cm^3 for atmospheres free of interferences (NIOSH, 1994). Using PLM, fibre concentrations below 0.001 fibre/cm^3 have been measured (Schneider, 1986).

For routine analysis, SEM allows good visualization of fibres as thin as 0.05 μm (WHO, 1996). The percentage of visible fibres starts to decrease as fibre width decreases below 0.3 μm. These figures vary according to the substrate, type of instrument and display mode (Kauffer *et al.*, 1993).

(iv) *Quality assurance*

During their exposure survey for the European epidemiological study (see section 2), Cherrie *et al.* (1988) found that use of the WHO PCOM method, combined with participation in interlaboratory workshops and slide exchanges, reduced the difference between participating laboratories from a factor of 3 to 1.4. Their fibre counting level increased by a factor of 3 and the exposure data have been corrected accordingly. For another participating laboratory, the increase in fibre counting was by a factor of 4.5.

(*e*) *Surface deposition*

Particles deposited on the skin or on horizontal surfaces in buildings can be removed using sticky foils (e.g. adhesive tape) and analysed by optical microscopy (Cuypers *et al.*, 1975; Schneider, 1986). Mucous threads and clumps from the inner corner of the eye can be used to estimate particle deposition in the eyes (Schneider & Stokholm, 1981).

(*f*) *Bulk material*

The diameter distribution of bulk material can be uniquely characterized by using the length-weighted (also termed ‘accumulated length’) diameter distribution. By this method, a bulk sample is heated to remove organic binder and oil and is comminuted. A small fraction is prepared for analysis by optical or electron microscopy. The length of the fibres within each given diameter interval (but not the total fibre number) is determined. The median is called the nominal diameter of the material. This distribution can also be determined using the intercept method (Schneider & Holst, 1983) by which diameters are measured for all fibres intercepting a line. Since the probability of intercepting the line is proportional to fibre length, this gives the length-weighted distribution.

To quantify the fibre diameter distribution of a wool product, typically a large number of fibres from the product are measured individually, using either optical microscopy or SEM. If the average fibre diameter is > 1 μm, the two techniques give comparable results. If it is appreciably less, the resolution of the optical microscope is insufficient, and the SEM results are more accurate (TIMA, 1993).

Analytical methods for MMVFs in bulk material have been developed by the industry and are based on optical microscopy (Koenig *et al*., 1993) and specific techniques for refractory ceramic fibres are based on SEM (Alexander *et al*., 1997).

1.2 Production

1.2.1 *History and production levels*

Most of the MMVF produced worldwide is used as insulation. For at least the last decade, glass wool, rock (stone) wool and slag wool have together met just over half of the world demand for insulation, with the remainder consisting of foamed plastics such as polyurethanes and polystyrenes and other minor products (cellulose, perlite, vermiculite, etc.). About 75% of the world's insulation material is produced and used in North America and Europe (the Freedonia Group, 2001).

World demand for glass, rock (stone) and slag wool insulation for selected years and by region is presented in Table 8. Approximately 88% of glass wool and 80% of rock (stone) and slag wool are used in the construction of residential and commercial buildings, and 12% of glass wool and 20% of rock (stone) and slag wool are used in industrial applications, including heating, ventilation and air conditioning, household appliances and transportation (the Freedonia Group, 2001).

(*a*) *Continuous glass filament*

The production of continuous glass filament which began in the 1930s (TIMA, 1993; Vetrotex, 2001) is one of the smallest segments of the glass industry in terms of tonnage. The USA is the biggest producer accounting for over 40% of worldwide output; Europe and Asia each produce 20–25% of the total. Twenty-six furnaces were in operation in the European Union in 1997, producing 475 000 tonnes of continuous glass filament (Table 9) (EIPPCB, 2000).

(*b*) *Glass wool, rock (stone) wool and slag wool*

Insulation products made from rock (stone) and slag wool were first produced around 1840 in Wales (Mohr & Rowe, 1978). By 1885, commercial manufacturing plants for rock (stone) wool were also operating in England and later spread to Germany and the USA (IARC, 1988). Glass wool was not produced commercially until the late 1930s and early 1940s (Mohr & Rowe, 1978).

Although some rock (stone) and slag wool plants were already operating in the USA and throughout Europe by the 1900s, the industry did not begin to grow until after the First World War. By 1928, at least eight plants operated in the USA. By 1939, the number of glass, rock (stone) and slag wool plants in the USA had increased to more than 25 (IARC, 1988).

Table 8. World demand for insulation

	1989	1994	1999
World demand for insulation[a] (thousand tonnes)	8564	9060	10 683
Rock (stone) and slag wool (thousand tonnes)	2641	2738	3090
Glass wool (thousand tonnes)	2646	2800	3493

Demand for rock (stone)/slag and glass wool insulation by region

	Rock (stone)/ slag	Glass	Rock (stone)/ slag	Glass	Rock (stone)/ slag	Glass
North America	223 (8.4%)	1508 (56.9%)	208 (7.6%)	1542 (55.1%)	236 (7.6%)	1915 (54.8%)
Western Europe	1195 (45.2%)	690 (26%)	1259 (46%)	757 (27%)	1374 (44.5%)	812 (23.2%)
Rest of the world	1223 (46.3%)	450 (17%)	1271 (46.4%)	500 (17.9%)	1480 (47.9%)	770 (22%)

[a] From the Freedonia Group (2001)

[a] All types of insulation, including rock (stone), slag and glass wools, foamed plastics and other minor products

Table 9. Glass filament production in the European Union in 1997

	No. of plants	No. of furnaces	Percentage of total European Union production
Northern Europe	5	10	43
Finland	1	3	
Germany	1	1	
Netherlands	1	2	
United Kingdom	2	4	
Central and southern Europe	7	16	57
Belgium	2	7	
France	2	4	
Italy	2	3	
Spain	1	2	
Total	12	26	475 000 tonnes

From EIPPCB (2000)

Glass fibre manufacturers opened new markets such as textile manufacturing, while rock (stone) wool and slag wool manufacturers continued to supply the thermal insulation market. The number of rock (stone) wool and slag wool plants in the USA peaked at between 80 and 90 in the 1950s and then declined as glass wool began to be used more in thermal insulation. In Europe, rock (stone) wool plants predominated until the mid-1970s when glass wool use increased (IARC, 1988). Table 10 gives the number of plants in various areas in 2000, and the volumes of MMVFs produced by these plants are presented in Table 11.

(*c*) *Refractory ceramic fibres*

Refractory ceramic fibres were first produced in the USA in the 1940s for the aerospace industry. The commercial importance of refractory ceramic fibres increased during the 1970s when rising energy costs created a strong demand for efficient refractory insulating products (Schupp, 1990; Maxim *et al*., 1994).

Although refractory ceramic fibre is a refractory insulating product with a defined market niche, the annual volume produced worldwide is relatively small (1–2% of the total production of MMVFs) (National Research Council, 2000). Table 12 shows estimates of capacity for refractory ceramic fibre production by region and by country for the year 1990 (Monopolies and Mergers Commission, 1991). In 2000, the world market for refractory ceramic fibres was estimated to be 150 000–200 000 tonnes per year; the market was divided approximately equally between the Americas, Europe and the rest of the world (NAIMA/EURIMA, 2001).

Table 10. Number of plants manufacturing glass wool, rock (stone) wool and slag wool in selected regions

Location	Glass wool	Rock (stone) wool and slag wool
Australia and New Zealand	4	1
Canada	8	3
Europe	30	30[a]
Japan and China	6	8
USA	32	12

From NAIMA/EURIMA (2001)
[a] Includes manufacture of high-alumina, low-silica wools

Table 11. Volume of glass wool, rock (stone) wool and slag wool manufactured in selected regions (thousand tonnes)

Location	Year	Glass wool	Rock (stone) wool and slag wool
Australia and New Zealand	2000	42	6
Europe	2000	1300	1200[a]
Japan and China	1999	223	342
USA	2000	1950	746

From NAIMA/EURIMA (2001)
[a] Includes manufacture of high-alumina, low-silica wools

(*d*) *Newly developed fibres*

In recent years, newer fibres, often with reduced biopersistence, have been developed for specific purposes. Examples include the high-alumina, low-silica (HT) wools, more than 1 million tonnes of which were produced for the European market in 2000 (Rockwool International, 2001) and the alkaline earth silicate (AES) wools, 10–20 thousand tonnes of which were produced in Europe in 2000 (ECFIA & RCFC, 2001).

1.2.2 *Production methods*

Figure 2 is a generic representation of the processes involved in producing MMVFs.

The technological changes that have occurred in the MMVF industry had the potential to affect the distribution of diameters in the bulk material, the propensity of the product to release fibres, the production rate and the extent of manual handling of

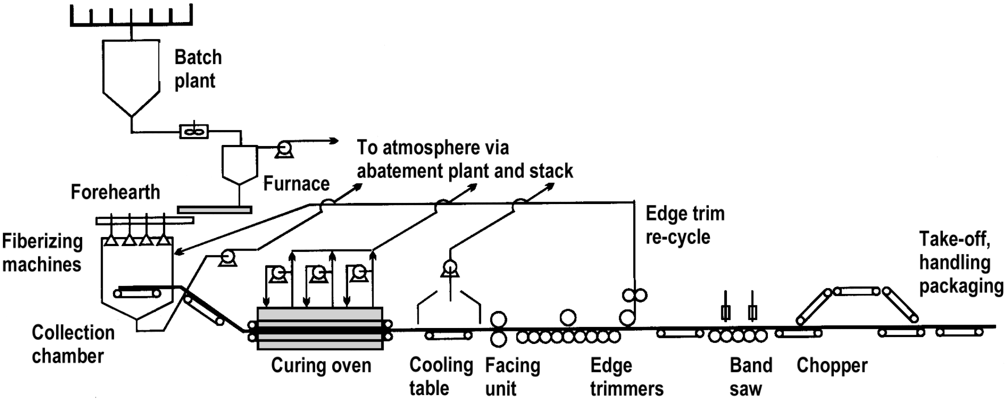
Table 12. Estimated production capacity for refractory ceramic fibres by region and country in 1990

Region	Country	Production capacity (thousand tonnes)	Percentage of subtotal	Percentage of total
East Asia and Oceania	Australia	3.10	11.0	2.0
	India	3.50	12.4	2.2
	Japan	17.50	62.1	11.0
	Malaysia	0.90	3.2	0.6
	Republic of Korea	2.30	8.2	1.4
	Taiwan, China	0.90	3.2	0.6
Subtotal		28.20		17.77
Europe	Former Czechoslovakia	1.60	3.0	1.0
	France	21.50	39.8	13.6
	Germany	7.90	14.6	5.0
	Hungary	1.20	2.2	0.8
	Italy	1.50	2.8	0.9
	Poland	2.20	4.1	1.4
	Spain	1.60	3.0	1.0
	United Kingdom	15.00	27.8	9.5
	Former Yugoslavia	1.50	2.8	0.9
		54.00		34.0
Subtotal				
USA and Canada	Canada	2.00	4.3	1.3
	Puerto Rico	2.75	6.0	1.7
	USA	41.40	89.6	26.1
Subtotal		46.15		29.1
Latin America	Brazil	4.75	51.1	3.0
	Mexico	3.80	40.9	2.4
	Venezuela	0.75	8.1	0.5
Subtotal		9.30		5.9
Other	China[a]	7.50	35.7	4.7
	South Africa	3.50	16.7	2.2
	Former Soviet Union[a]	10.00	47.6	6.3
Subtotal		21.0		13.2
Total		158.65		100.0

Secondary source: Monopolies and Mergers Commission (1991) citing Morgan Crucible estimates

[a] Countries for which these estimates are less reliable

Figure 2. Schematic of a typical MMVF manufacturing plant



From EIPPCB (2000)

the products. Such changes may have resulted in qualitative differences in the concentrations of airborne fibres and may thus have affected exposure levels. For epidemiological purposes, three technological phases in the history of the European insulation wool manufacturing industry have been defined between the 1930s and the 1970s (Dodgson *et al.*, 1987a):

(i) the early phase, corresponding to periods when MMVFs were manufactured by discontinuous batch production and/or oil was not added during production;

(ii) the late phase, corresponding to modern production techniques including the addition of oil; and

(iii) the intermediate phase which included all the mixed production processes excluded by definition from (i) and/or (ii).

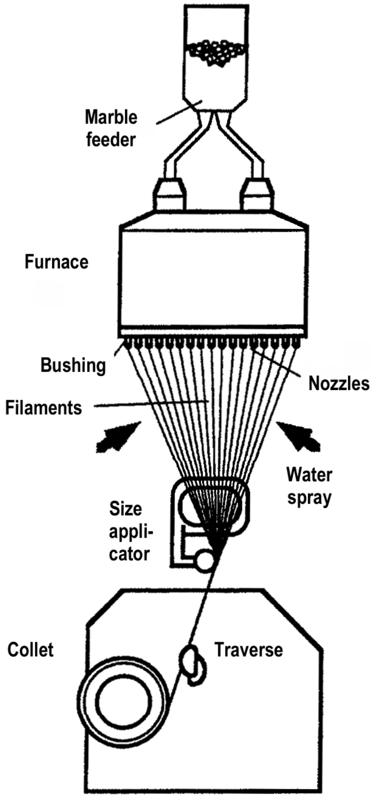
The timing of the three phases differs between the ten manufacturing plants surveyed by Dodgson *et al.* (1987a), so that for the industry as a whole, the early phase spans the period from 1933–68, the intermediate phase from 1940–69, and the late phase from 1951–78 (the last year included in the study).

The history of the production of glass, rock (stone) and slag wool and refractory ceramic fibres in the USA has essentially paralleled the development of the fiberization process. The steam-blown process that was initially used to produce MMVFs was quickly replaced by the flame attenuation process in the mid-1940s. The spinning process was introduced in the mid-1950s and was further enhanced in the rotary process that was introduced in the late 1950s and remains the primary means of fibre production today (Mohr & Rowe, 1978; TIMA, 1993). Lubricating oils and mineral oils were used in the manufacturing process from its inception. The early binder formulations contained inorganic minerals (e.g. clay) and petroleum-based mixtures, but these were rapidly replaced in the mid 1940s and early 1950s by the phenol–formaldehyde system which has been used predominantly ever since (TIMA, 1993).

(*a*) *Continuous glass filament*

To produce continuous glass filament, the raw materials are mixed together, or supplied as pre-formed marbles, and melted in a gas-fired or electrically-heated furnace. The resulting glass then flows from the front end of the furnace through a series of refractory-lined, gas-heated channels to the forehearths. Along the bottom of each forehearth are bushings, complex box-like structures made of precious metal, and at the base of the bushing is a metal plate perforated with several hundred calibrated holes called bushing tips. As illustrated in Figure 3, the glass flowing through the bushing tips is drawn out and attenuated by the action of a high-speed winding device to form continuous filaments. Specific filament diameters in the range of 5–24 µm are obtained by precise regulation of the linear drawing speed. Directly under the bushing, the glass filaments are cooled rapidly by the combined effect of water-cooled metal fins, high airflow and water sprays. The filaments are drawn together and pass over a roller or belt, which applies a protecting and lubricating coating, called size.

Figure 3. Continuous drawing process for manufacturing textile fibres



From TIMA (1993)

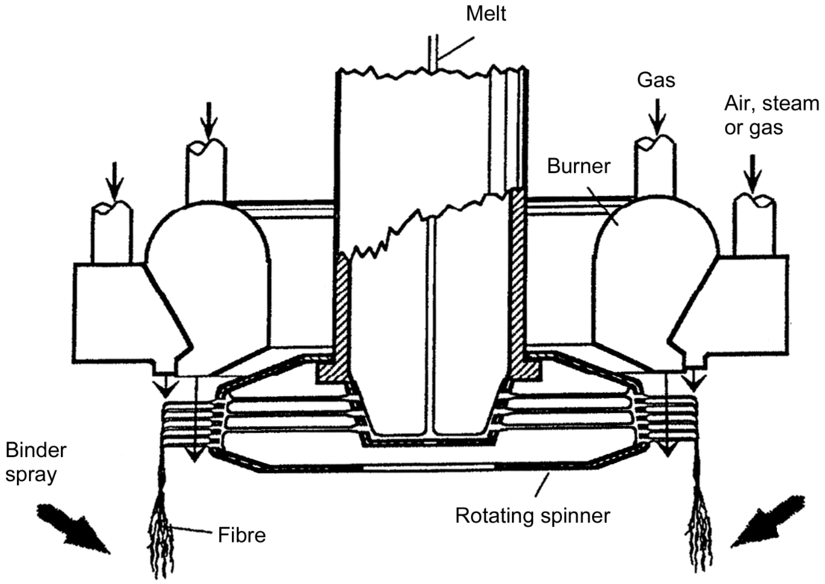
The coated filaments are gathered together into bundles called strands that are further processed (e.g. by chopping, twisting, milling and/or the application of binder), depending on the type of reinforcement being made as end-use. The typical products of these processes include continuous and chopped strand mat, yarns, roofing or surface tissue, rovings and roving cloths (EIPPCB, 2000).

(*b*) *Glass wool*

During the production of glass wool by the rotary process, raw materials are blended and melted in an electrically heated furnace, an oxy-gas furnace or a traditional refractory-lined, gas-fired recuperative furnace. As depicted in Figure 4, a stream of molten glass flows from the furnace along a heated refractory-lined forehearth and pours through a number of single-orifice bushings into specially designed rotary centrifugal spinners. Primary fiberizing is the result of the centrifugal action of the rotating spinner; fibres are further attenuated by hot gases from a circular burner. This forms a veil of randomly interlaced fibres with a range of lengths and diameters. The veil passes through a ring of binder sprays that deposit a phenolic resin binder and mineral oil onto the fibres to provide integrity, resilience, durability and handling quality to the finished product (EIPPCB, 2000).

The resin-coated fibre is drawn under suction onto a moving conveyor to form a mat of fibres. This mat passes through a gas-fired oven, which dries the product and

Figure 4. Rotary process for manufacturing glass wool fibres



From TIMA (1993)

cures the binder. The product is then air-cooled and cut to size before packaging. Fibres trimmed from the edges can be granulated and blown back into the fibre veil, or combined with surplus product to form a loose wool. Some glass wools are produced without oven curing, (e.g. microwave-cured, hot-pressed, uncured or binder-free products). Also, certain laminated products are made by the application of a coating (e.g. aluminium foil or glass tissue) which is applied with an adhesive (EIPPCB, 2000).

A range of secondary products can be made from manufactured glass fibre. These include granulated insulation wool for installation by blowing, packaged uncured wool for supply to customers for further processing, and laminated or faced products. Pipe insulation is a significant secondary product that is usually manufactured by diverting uncured wool from the main process for press moulding and curing (EIPPCB, 2000).

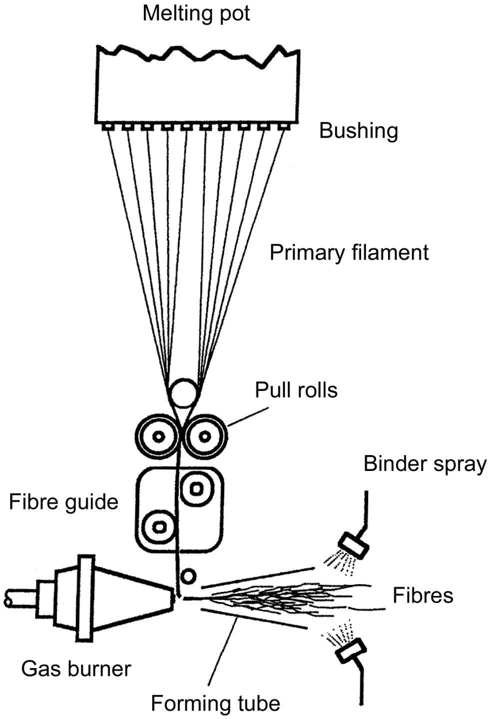
Special-purpose fibres

Glass wool can also be made by the flame attenuation (pot and marble) process, which is more commonly used for the production of special-purpose fibres. This is a two-step process as shown in Figure 5. First, a coarse primary filament is drawn from a viscous melt. The coarse fibre is then remelted and attenuated into many finer fibres using a high-temperature gas flame, normally mounted at right angles to the primary fibre. Fibres are usually propelled by the high-velocity gases through a forming tube, where they are sprayed with a binder, and then to a moving collection chain where they deposit and tangle, producing a mat which is further processed into a variety of special application and filtration products (TIMA, 1993).

(*c*) *Rock (stone) wool*

The first step in the manufacture of rock (stone) wool is to melt a combination of alumino-silicate rock (usually basalt), blast furnace slag and limestone or dolomite. The batch may also contain recycled process or product waste. The most common melting apparatus is the coke-fired hot-blast cupola. The cupola consists of a cylindrical steel mantle which may be refractory-lined and closed in at the bottom. The cupola is charged to the top with raw materials and coke. Oxygen-enriched air is injected into the combustion zone, 1–2 m from the bottom of the cupola. The molten material gathers in the bottom of the furnace and flows out of a notch and along a short trough from where it falls onto the rapidly rotating wheels of the spinning machine and is thrown off in a fine spray, producing fibres (Figure 6). Air is blasted from behind the rotating wheels to attenuate the fibres and to direct them on to the collection belt. Binder (an aqueous phenolic resin solution) is applied to the fibres by a series of spray nozzles on the spinning machine. The primary mat is layered to give the product the required weight per unit area, and passes through an oven, which sets the thickness of the mat, dries it and cures the binder. The product is then air-cooled and cut to size before packaging (EIPPCB, 2000).

Figure 5. Flame attenuation process for manufacturing special-purpose glass fibres



From TIMA (1993)

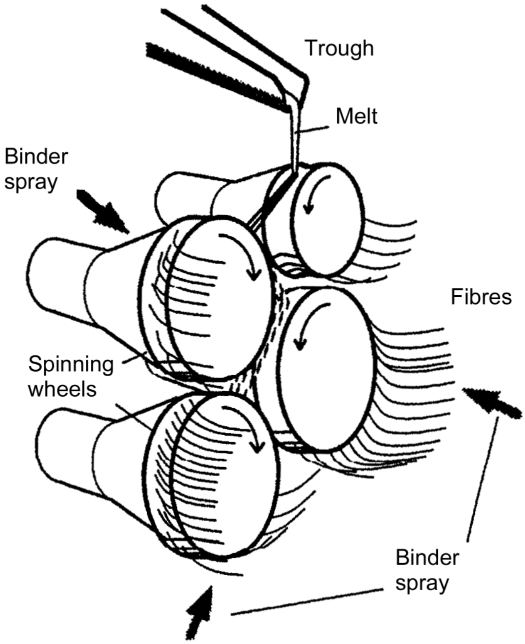
Pipe insulation and some secondary products may be manufactured by the process described for glass wool (EIPPCB, 2000).

Rock (stone) wool can also be produced using immersed electric arc furnaces (graphite electrodes) and flame furnaces. The subsequent operations including fibrization are the same as described above (EIPPCB, 2000).

(*d*) *Slag wool*

The production of slag wool is similar to that of rock (stone) wool. Slag wool is made by melting the primary component, blast furnace slag, with a combination of inorganic additives. The batch may also contain recycled process or product waste. As with rock (stone) wool, the most common melting apparatus is the coke-fired cupola, but immersed electric arc furnaces and flame furnaces may also be used. The subsequent process operations including fibrization are the same as for the production of rock (stone) wool (EIPPCB, 2000).

Figure 6. Wheel centrifuge or spinning process for manufacturing rock (stone) and slag wool and some refractory ceramic fibres



From TIMA (1993)

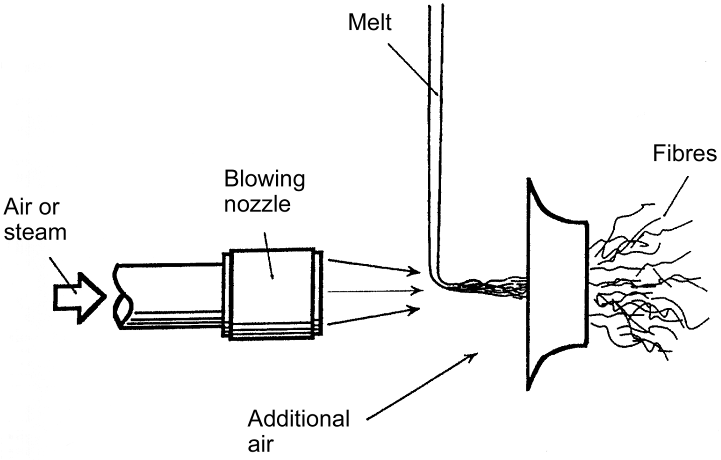
(*e*) *Refractory ceramic fibres*

Refractory ceramic fibres are produced by melting a combination of alumina and silica in approximately equal proportions at temperatures up to 2000 °C or in the USA by melting kaolin clay together with several trace ingredients. The molten mixture is made into fibre either by blowing an air stream on to the molten material flowing from an orifice at the bottom of the melting furnace (the blowing process; Figure 7), or by directing the molten material into a series of spinning wheels (the spinning process; Figure 6). The fibres are either collected directly as bulk fibre, or further processed into a blanket by a needling process. Although refractory ceramic fibres are sold in a variety of forms, all start with the production of either bulk or blanket material, termed 'primary refractory ceramic fibre production' (TIMA, 1993; EIPPCB, 2000).

The physical properties of the refractory ceramic fibre produced vary according to the method of fibrization. Spun fibre, for example, usually has a higher average diameter than blown fibre (TIMA, 1993).

The processing of refractory ceramic fibres begins with the fibre in either bulk or blanket form. Bulk material may be used directly, but is usually used as a feedstock for other processes. Bulk material can be converted into paper, board, felt, textiles, vacuum-formed products or dispersed in a fluid or solid matrix for other applications.

Figure 7. Fibre blowing process for manufacturing refractory ceramic fibres



From TIMA (1993)

The blanket form is often used directly (e.g. as a furnace insulation material), but may be fabricated into modules, gaskets and other products. These 'downstream' processing operations may be carried out in the plants of the primary producers or in plants operated by other firms (EIPPCB, 2000).

(*f*) *Newly developed fibres*

Alkaline earth silicate (AES) wools are made using the same equipment that is used to manufacture refractory ceramic fibres, although the different compositions of refractory ceramic fibres and AES wools result from very different operating conditions for furnacing and fibrization.

The high-alumina, low-silica fibres are produced by processes similar to those described for rock (stone) wool, but briquettes (artificial stones) containing fine-grained raw material with a high melting point such as quartz sand, olivine sand and bauxite are used as starting materials (Guldberg *et al.*, 2002).

1.3 Uses

1.3.1 *Continuous glass filament*

Continuous glass filament products are used in a broad variety of applications, but their main end-use (approximately 75%) is as reinforcements in composites with thermosetting or thermoplastic resins. The main markets for composite materials are the automotive and other transport industries, the electrical and electronics industry and the building industry. Around 50% out of the sector output goes into the building and automotive/transport industries (EIPPCB, 2000).

Chopped strand mats are used to reinforce thermoplastics in the construction of boat hulls and decks, vehicle bodies, sheeting and storage tanks. Continuous strand mats are used in laminate production, when press moulding is employed, and to improve the appearance and strength of the laminates. Rovings have a variety of uses. They may be chopped to make chopped strands, woven into roving cloth or wound onto a mould for making convex-shaped composites such as nose cones for aeroplanes. Rovings are also used to reinforce plastic parts and in applications that require electrical insulation. In addition to being used as a reinforcement in thermoplastics, chopped fibres are used as a reinforcement in roof mat, which is commonly used to cover concrete or wooden roofs. Glass fibre mat is also used as a reinforcement in vinyl floor tiles and sheet linoleum floor covering (Loewenstein, 1993). Glass fibre yarns are used in the manufacture of glass cloth and heavy-duty cord for tyre reinforcement. The main market for glass textiles is the electronics industry where they are used in the production of high-quality printed circuit boards (EIPPCB, 2000). Other important uses are for aeroplane structures and for fireproof textiles, such as draperies and emergency protective clothing (IARC, 1988).

1.3.2 Glass wool, rock (stone) wool and slag wool

Figure 8 shows the main uses of glass, rock (stone) and slag wools.

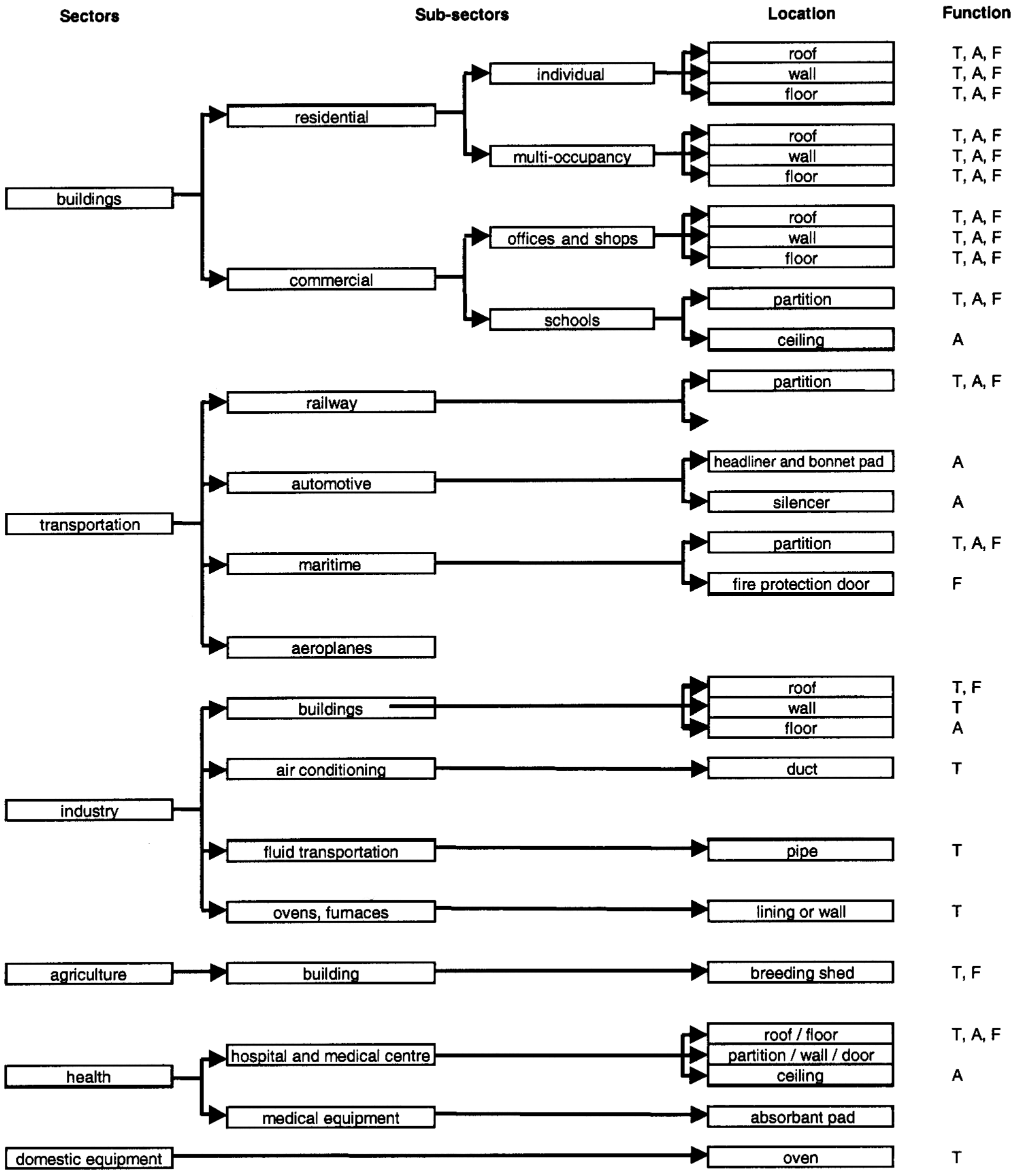
(*a*) *Thermal and acoustic insulation, fire protection*

Whatever the method employed to manufacture glass, rock (stone) or slag wools, the small-diameter, stiff, tangled fibres of these vitreous wools form a spongy mass, in which millions of small air pockets are trapped. These air pockets create an effective barrier against the transmission of both heat and sound energy. Therefore, glass, rock (stone) and slag wools provide effective thermal insulation for buildings (i.e. they help to keep buildings warm in the winter and cool in the summer). Many different areas of the home may be protected thermally: ceilings, side walls, perimeters of slabs, floors and other areas. Sound reduction is also an important use of glass, rock (stone) or slag wools, not only in buildings, but also in appliances, machinery and air-handling systems.

The insulation of homes, other buildings and industrial processes against heat loss and heat gain represents the largest single use for glass, rock (stone) and slag wools; up to 70% of industry output is for these applications (EIPPCB, 2000). Vitreous wools can be blown into structural spaces, such as in walls and attics. Bulk rock (stone) wool and glass fibre rovings are incorporated into ceiling tiles to provide fire resistance and thermal and sound insulation. Batts, blankets and semi-rigid boards made of glass, rock (stone) or slag wool fibres are used in both residential and commercial buildings. Pipe and board insulation is used extensively in industrial processes.

Sound absorption: Glass, rock (stone) or slag wool insulation in partitions, floors and ceilings significantly reduces sound transmission.

Figure 8. Main uses of glass, rock (stone) and slag wools



Modified from various industry sources.
T, thermal; A, acoustic; F, fire protection

Ceiling tiles and wall panels: Ceiling tiles and wall panels that serve as acoustical and thermal insulators can be made from glass, rock (stone) or slag wools.

Pipe and air-handling insulation: Glass, rock (stone) or slag wool can be used to insulate cold and hot pipes both indoors and outdoors and in many climates. They are also used on sheet-metal ducts and plenums for thermal and acoustical insulation, resulting in quieter and more energy efficient heating and air conditioning systems.

Appliance and equipment insulation: Glass, rock (stone) or slag wools are effective thermal and acoustical insulators and improve energy efficiency in many electrical appliances and other types of machinery.

Transportation insulation: Vehicles or carriers (cars, ships, aircraft and spacecraft are fitted with glass wool insulation to enhance their performance and to provide the required thermal and acoustic conditions for the goods or passengers being transported. Glass wool and rock (stone) wool are also used in sound-absorbent barrier panels alongside motorways and railways.

(*b*) *Other uses*

Glass wool and rock (stone) wool are used as growing media and for soil conditioning in agriculture (EIPPCB, 2000), especially for vegetables and flowers. Rock (stone) wool mats are used for insulation of railway and tramway tracks against vibration.

(*c*) *Special-purpose glass fibres*

The largest market for special-purpose glass wool is in battery separator media. The primary component of such media is an acid-resistant borosilicate glass fibre with an average fibre diameter ranging from 0.75–3 μm. The purpose of the media is the physical separation of the positive and negative plates within the battery, while enabling the sulfuric acid electrolyte to pass through the media and the filtration of impurities (TIMA, 1993).

Glass fibre is widely used as a filtration medium because it has unique properties, such as strength and non-hygroscopicity. Papers made from very thin-diameter fibres (average fibre diameter 0.1–1 μm) are used for high-efficiency air filtration media (TIMA, 1993).

1.3.3 *Refractory ceramic fibres*

The important physical properties of refractory ceramic fibres are their relatively high (1000–1460 °C) maximum use temperature (EIPPCB, 2000), low thermal conductivity, very low thermal mass (low bulk heat capacity), resistance to thermal shock and low density (light weight). Refractory ceramic fibres are produced and sold in a variety of physical forms, including bulk, blanket, felt, modules, board, vacuum-formed shapes, mixes, cements, putties and textile. The main applications and product characteristics vary with the product form (Table 13).

Table 13. Major applications of refractory ceramic fibres

Product form	Major applications	Product characteristics
Blanket, felt, modules	Furnace, kiln lining; firewall protection; high-temperature gaskets and seals for expansion joints; turbines; insulation wraps	Low thermal conductivity; flexibility; strength
Bulk	Fill-in packaging material for expansion joints; furnace base seals; conversion to other forms	Resilience
Board	Expansion joints; furnace, kiln back-up insulation; furnace lining; heat shields	Resilience, rigidity, resistance to high air velocity
Paper	Thermal, electrical insulators; refractory backup; ingot mould linings	Low thermal conductivity, dielectrical properties
Vacuum-formed shapes	Furnace linings (boards), insulation for special foundry components	Variable
Mixes, textiles (cloth, rope, sleeving) and miscellaneous	Patching refractory cracks and fissures; composite insulation for space firings and launchings; cloth (furnace curtains, welding curtains and blankets); sleeving (tube protection, cable insulation)	Resilience, insulating properties

From ECA (1996)

Refractory ceramic fibres are used chiefly in industrial applications; they have few consumer uses. In the USA, the largest percentage of the demand for refractory ceramic fibres (63%) in 1990 was for furnace lining and related applications (ECA, 1996). According to the estimates of the MMVF industry in the USA, six key sectors of the economy: ceramics, glass, forging, hydrocarbon processing, aluminium and steel consume 70–80% of the refractory ceramic fibres used for furnace lining and related applications.

Table 14 provides estimates of the percentages of the European refractory ceramic fibre market accounted for by various applications (ERM, 1995); furnace applications are the largest single market (50%). Data on markets and applications for refractory ceramic fibres in other areas of the world are not readily available, but they are believed to be similar to those in Europe and the USA (Horie, 1987).

Examples of applications of refractory ceramic fibres include: appliances (water combustion chambers, hearth products, fireplace logs, stove tops), automotive uses (catalytic converters, brake pads, air bags, heat shields), chemical applications (ethylene furnace insulation, reformer insulation, crude heaters), fire protection (temperature-resistant door lining, chimney liners, expansion joints), iron and steel incinerators (ladle preheat stands and covers, continuous casters, reheat furnaces, coke ovens), non-ferrous

Table 14. The European market for refractory ceramic fibres by application

Application	Proportion of the market (per cent)
Furnace, heater and kiln linings	50
Appliances	20
Metal processing (excluding furnace linings)	10
Automotive uses	5
Fire protection	5
General industrial insulation	10

From ERM (1995), citing estimates prepared by ECFIA

metal incinerators (soaking pit covers, melting furnaces), power generation (co-generation systems, turbine exhaust duct work, heat recovery steam generators, various types of boiler), aerospace and defence (heat shields) (Horie, 1987; ICF, Inc., 1991; ERM, 1995; ECA, 1996).

1.3.4 *Newly developed fibres*

Alkaline earth silicate wools generally have the same market applications as refractory ceramic fibres. However, although AES wools tolerate continuous service temperatures above those of rock (stone) wool and slag wool, they are below those tolerated by refractory ceramic fibres and therefore AES wools cannot be substituted for refractory ceramic fibres in all applications.

High-alumina, low-silica wools are now widely used in the same applications as rock (stone) wool.

1.4 Occurrence

1.4.1 *Occupational exposure*

The extent to which exposure to MMVFs occurs during their manufacture, fabrication, installation and end-use has been the subject of reviews and reports for some time. The European CAREX database (Kauppinen *et al.*, 2000) estimated that approximately 930 000 workers were exposed to glass wool and/or continuous glass filament, and 62 000 to refractory ceramic fibres in the European Union in 1990–93.

In the late 1960s, exposure to MMVFs was evaluated as total dust (gravimetric) concentrations (i.e. mg/m^3) as a result of the then existing regulatory requirements and the limitations of the sampling and analytical equipment available at the time (see section 1.1.3). However, the critical evaluation of exposure data collected using this methodology (Corn & Sansone, 1974; Corn *et al.*, 1976; Esmen *et al.*, 1978, 1979a,b;

Head & Wagg, 1980) revealed that for a given exposure reported in mg/m^3, considerable variation in the concentration of airborne fibres was possible depending on the mean aerodynamic diameter of the fibres being evaluated, and the presence of other particulate matter in the environments being studied.

Thus, sampling and evaluation of exposure to MMVFs came to rely on fibre counts made using optical and electron microscopy (Taylor, 1977; Eller, 1984; WHO, 1985). These became the conventional means of reporting the extent of the exposure of individuals to fibres in occupational environments. These methods were based on an explicit definition of what constituted a fibre (see section 1.1.3) and reported the results in fibres/cc (i.e. fibres/cm^3 or fibres/mL); they had the advantage not only of standardizing the approach to fibre monitoring, but also producing results in terms of 'respirable' fibres only. This is significant because, as discussed more fully in section 4.1, airborne fibres with diameters of 3 μm or less are currently thought to be the most likely to have adverse effects on human health.

Considerable quantities of data were obtained using these standardized methods for the evaluation and reporting of exposure to MMVFs in the MMVF manufacturing and installation industries. These data gave relatively consistent results from one MMVF product type to another irrespective of the geographical location of the manufacturing or installation site. For this reason, the MMVF exposure data presented here report the results in fibres/cm^3 only.

Certain factors must, however, be considered when interpreting the results of individual studies or comparing the results of two or more of the studies described below. The length of the fibre sampling period (i.e. full-shift or short-term) as well as the sample type (i.e. personal or area) is significant. Similarly important are the fibre counting methods and the type of microscopy (i.e. PCOM, TEM or SEM) used for sample analysis. As noted above, fibre counting methods and microscopy techniques have evolved over time, and the results obtained using the NIOSH P & CAM 239 method (Taylor, 1977) in the 1970s and early 1980s are not directly comparable to those obtained using the WHO method and the NIOSH 7400 (B counting rules) method (Eller, 1984) from the late 1980s onwards (WHO, 1996).

The manner in which the data on MMVFs is presented or summarized in each study is also significant when interpreting the results. Arithmetic means or medians with standard deviations and sample ranges have been reported in some studies while geometric means with geometric standard deviations were given in others. In common with most other types of occupational exposure, the concentrations of airborne fibres are better described by a log-normal than a normal distribution (Leidel *et al.*, 1977). In contrast to normally distributed data sets which tend to follow traditional Gaussian (i.e. bell shaped) distributions, log-normal data sets are generally positively skewed (long 'tail' to the right) indicating a larger probability of very high individual exposure concentrations than would be the case for normally distributed data sets. Geometric means are the preferred method of expressing central tendency for log-normally distributed data sets, and are usually smaller and more similar to arithmetic medians than to arithmetic means for a given set of data. Each study presented in section 2 should thus be carefully interpreted to determine the influence of each of these factors, individually or in combination, on the results.

Exposure is normally determined principally by counting airborne fibres, but for the complete characterization of fibre sizes the joint values of diameter and length of each fibre should also be determined. The size distribution of a population of fibres characterized in this way can be summarized by count geometric mean, GM, and geometric standard deviation, GSD, of diameter, D, and length, L, and the correlation between $\log_e(D)$ and $\log_e(L)$, CORR. If the distribution is bivariate log-normal, these five parameters will completely specify the size distribution (Schneider, 2000). Table 15 presents the data on the sizes of airborne fibres analysed by electron microscopy in several studies.

(*a*) *Exposure in production plants*

(i) *United States of America*

Among the earliest evaluations of the exposure of workers in MMVF production facilities in the USA was a survey conducted by Johnson *et al.* (1969) of five glass fibre factories, four of which manufactured insulation material and one that produced textile (i.e. continuous glass filament) fibres. The results were reported in terms of both gravimetric (i.e. mg/m^3) and airborne fibre (i.e. fibre/cm^3) concentrations. The concentrations of airborne fibres longer than 5 μm ranged from 0.0–0.97 fibre/cm^3 in the insulation plants and from 0.0–1.97 fibre/cm^3 in the textile fibre plant. From the results presented in Table 16, the authors of the survey concluded that exposure was low when compared with that measured for similar operations performed in the asbestos processing industry at the time.

In a follow-up of this work, Dement (1975) surveyed concentrations of airborne fibres in four glass fibre facilities that manufactured 'large-diameter' (i.e. most fibre diameters > 1 μm) insulation products and six facilities that produced and/or used 'small-diameter' (i.e. most fibre diameters < 1 μm) fibre products. One facility that manufactured glass-fibre reinforced products was also surveyed. The results of the analysis of air samples taken at the plants where 'large-diameter' glass fibre insulation was produced were classified according to the fibre-forming method and fabrication operations within each plant. The mean and range for concentrations of airborne fibres is shown in Table 17. The highest mean concentration of fibres measured in these facilities was 0.20 fibre/cm^3 in the 'all other operations' category of plant C. The results of the analysis of air samples taken at the facilities that produced and used 'small-diameter' glass fibre were grouped according to product type and fabrication operations within each plant. The mean and range for concentrations of airborne fibres measured at these plants is shown in Table 18. In contrast to the results seen in the plants where 'large-diameter' glass-fibre insulation was produced, the mean concentrations of airborne fibres from 'small-diameter' glass fibre bulk-handling operations ranged from

Table 15. Bivariate size distributions of airborne fibres in various occupational settings summarized by various parameters

Reference	Type	Method	GM (D)	GSD (D)	GM (L)	GSD (L)	CORR
Cherrie *et al.* (1987)	Simulation of early rock (stone) wool production	SEM	0.3–0.5	1.9–2.7	7.0–9.0	2.2–3.0	0.4–0.6
Schneider *et al.* (1985)	Use of rock (stone) wool	SEM	1.2	2.7	22	4.0	0.7
	Use of glass wool	SEM	0.75	2.8	16	3.5	0.7
Breysse *et al.* (2001)	Use of glass wool	SEM	0.8–1.9	1.4–1.9	9.5–30	1.4–2.5	0.2–0.7
	Use of rock (stone) wool	SEM	1.6–1.9	1.6–1.9	19	1.7–2.7	0.4–0.6
Plato *et al.* (1995a)	House prefabrication: glass wool	SEM	0.91–1.2	1.7–1.8	9.2–9.3	2.3–2.5	–
	House prefabrication: rock (stone) wool	SEM	1.3–1.7	1.9	12–17	2.5–2.8	–
Lees *et al.* (1993)	Installation of MMVF batts	SEM	0.9–1.3	2.2	22–37	2.8–2.9	0.5–0.6
	Installation of loose MMVF with binder	SEM	1.0–2.0	1.8–2.2	30–50	2.3–2.6	0.4–0.6
	Installation of loose MMVF wool without binder	SEM	0.60	1.9	14–15	2.4–2.6	0.5–0.6
Maxim *et al.* (2000a)	RCF production and use	TEM[a]	0.84	2.1	14	2.5	0.4
Hori *et al.* (1993)	RCF, factory A	SEM-micrographs	0.96–1.2	1.7–1.9	12–19	2.4–2.6	–
	RCF, factory B	SEM-micrographs	0.86	1.9–2.0	11–13	2.4–2.6	–

GM, geometric mean; D, diameter; GSD, geometric standard deviation; L, length; CORR, correlation between $\log_e(D)$ and $\log_e(L)$; –, not determined; RCF, refractory ceramic fibre; SEM, scanning electron microscopy; TEM, transmission electron microscopy

[a] For analytical method, see Mast *et al.* (2000a)

Table 16. Fibre concentrations (fibre/cm^3) by plant and operation

Operations	Plant no.[a]	Total fibres		Fibre length > 5 µm		Fibre length > 10 µm	
		Mean	Range	Mean	Range	Mean	Range
Mixing and melting	1	–	–	–	–	–	–
	2	3.64	3.64	0.97	0.97	0.54	0.54
	3	0.66	0.41–1.03	0.16	0.10–0.26	0.08	0.02–0.16
	4	0.30	0.08–0.67	0.10	0.02–0.25	0.04	0–0.07
	1–4[b]	1.53	0.08–3.64	0.41	0.02–0.97	0.22	0–0.54
	5	0.09	0.09	0.04	0.04	0	0
Forming	1	–	–	–	–	–	–
	2	0.41	0.04–2.95	0.12	0–0.56	0.08	0–0.35
	3	0.15	0.02–0.45	0.04	0–0.14	0.02	0–0.09
	4	0.19	0.07–0.31	0.07	0.01–0.19	0.03	0–0.06
	1–4[b]	0.25	0.02–2.95	0.08	0–0.56	0.04	0–0.35
	5	0.10	0–0.19	0.02	0–0.04	0.01	0–0.04
Spinning, twisting and waste recovery	5	0.72	0.03–12.67[c]	0.11	0–1.97	0.01	0–0.06

From Johnson *et al.* (1969) (personal samples; 2–7 h sampling times; analysis by phase-contrast optical microscopy including fibres < 5 µm in diameter)

[a] Plants 1–4 are insulation manufacturing plants; Plant 5 is a textile manufacturing plant.

[b] Combined results for plants 1–4

[c] [The Working Group noted that this range is not reliable because of the difficulty of discriminating between vitreous fibres and other particles with the methodology used.]

Table 17. Concentrations of airborne fibres (fibre/cm^3) in wool insulation facilities manufacturing 'large-diameter' (> 1 µm) glass fibres

Forming method or operation	Insulation plant			
	A	B	C	D
Centrifugal-formed building insulation				
Mean	0.07	0.08	0.09	0.09
Range	0.04–0.13	0.00–0.18	0.08–0.12	0.01–0.83
Number of samples	9	19	4	22
Centrifugal-formed appliance insulation				
Mean	–	0.04	–	0.06
Range	–	0.01–0.11	–	0.02–0.09
Number of samples	–	13	–	22
Flame-attenuated insulation				
Mean	0.04	–	0.14	–
Range	0.02–0.06	–	0.04–0.24	–
Number of samples	8	–	2	–
Pipe insulation				
Mean	0.07	–	0.14	–
Range	0.03–0.12	–	0.06–0.27	–
Number of samples	10	–	6	–
Scrap reclamation				
Mean	0.06	0.07	0.10	0.07
Range	0.03–0.15	0.02–0.47	0.08–0.13	0.01–0.14
Number of samples	10	4	5	7
All other operations				
Mean	0.07	0.04	0.20	–
Range	0.01–0.13	0.01–0.08	0.04–0.26	–
Number of samples	10	12	4	–

From Dement (1975) (personal and stationary samples; analysed by PCOM)

1.0–21.9 fibres/cm^3; the highest fibre concentration observed was 44.1 fibres/cm^3 in plant G.

In the plant that produced glass-fibre reinforced plastics, the concentrations of airborne fibres ranged from 0.02–0.10 fibre/cm^3 with a mean concentration of 0.07 fibre/cm^3 for lamination operations and 0.03 fibre/cm^3 for cutting and grinding operations. Dement (1975) commented that the nominal diameter of the fibres produced was a principal factor in determining the concentrations of airborne fibres present.

The largest body of data on exposure of production workers in the USA was collected in support of an epidemiological study of the MMVF industry (Corn &

Table 18. Concentrations of airborne fibres (fibre/cm^3) in operations producing or using 'small-diameter' (< 1 μm) glass fibres

Operations	Plant					
	Bulk fibre production		Paper manufacture		Aircraft insulation fabrication	
	C[a]	E	F[b]	G[b]	H	P[b]
Bulk fibre handling						
Mean	1.0	9.7	5.8	21.9	1.2	14.1
Range	0.1–1.7	0.9–33.6	4.7–6.9	8.9–44.1	0.4–3.1	3.2–24.4
Number of samples	5	54	2	3	13	3
Fabrication and finishing						
Mean	–	5.3	1.9	10.6	0.8	2.1
Range	–	0.3–14.3	1.6–2.1	–	0.2–4.4	–
Number of samples	–	24	2	1	15	1

From Dement (1975) (personal and stationary samples; analysed by PCOM)

[a] In addition to producing 'large-diameter' wool insulation, plant C had several lines that produced 'small-diameter' fibres.

[b] Only limited surveys were conducted in these facilities.

Sansone, 1974; Corn *et al.*, 1976; Esmen *et al.*, 1978, 1979a) (see IARC, 1988). This study encompassed 16 glass wool, continuous glass filament, rock (stone) wool and slag wool plants. A summary of the concentrations of airborne fibres, measured using PCOM with counting criteria equivalent to those of the NIOSH A rule combined with TEM, is presented in Table 19. The mean fibre concentrations varied widely from plant to plant ranging from 0.001 fibre/cm^3 in the forming area of plant 10 to 1.56 fibres/cm^3 in the manufacturing area of plant 15. Esmen *et al.* (1978, 1979a) attributed these differences to the type of MMVF produced as well as to differences in manufacturing operations. However, most specifically, the concentrations of airborne fibres observed correlated closely to the nominal diameter of the fibres manufactured, as reported previously by Dement (1975).

Estimates of exposure to respirable fibres by plant during the manufacture of glass fibre (glass wool and continuous glass filament) were recently published by Smith *et al.* (2001). These estimates, shown in Table 20, were used in the epidemiological analysis of cause-specific mortality conducted by Marsh *et al.* (2001a) (see section 2).

When data from rock (stone) wool and slag wool manufacturing plants were evaluated separately, concentrations of airborne fibres were found to be slightly higher than those measured in glass-fibre manufacturing plants (Corn *et al.*, 1976; Esmen *et al.*, 1978). The average concentrations of airborne fibres varied from 0.01–0.42 fibre/cm^3 in one plant that produced slag wool and from 0.20–1.4 fibre/cm^3 in one that produced rock (stone) wool (see Table 21). Corn *et al.* (1976) suggested that the higher concentrations

Table 19. Concentrations of airborne fibres (fibre/cm^3), as determined by optical microscopy, in 16 MMVF plants in the USA

Plant no.	Forming[a]		Production[b]		Manufacturing[c]		Maintenance[d]		Quality control[e]		Shipping[f]		Overall	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	0.002	0.001	0.38	0.32	0.03	0.02	0.02	0.02	0.07	0.10	0.01	0.001	0.01	0.25
2	0.07	0.03	0.17	0.14	0.12	0.11	0.08	0.05	0.19	0.16	0.07	0.06	0.11	0.12
3	–	–	0.02	0.02	–	–	0.07	0.18	–	–	0.005	0.01	0.04	0.10
4	0.01	0.004	0.07	0.12	0.04	0.05	0.03	0.02	0.01	0.01	0.02	0.01	0.04	0.08
5	0.02	0.01	0.03	0.02	0.03	0.02	0.02	0.01	0.03	–	0.03	0.01	0.02	0.02
6	0.05	0.10	0.01	0.01	0.009	0.01	0.01	0.03	0.01	0.02	0.005	0.004	0.01	0.03
7	0.15	0.03	0.24	0.12	0.43	0.32	0.44	0.37	–	–	0.15	0.17	0.34	0.30
8	–	–	0.03	0.02	0.04	0.03	0.01	0.01	–	–	0.01	0.01	0.02	0.02
9	0.02	0.02	0.01	0.01	0.02	0.07	0.01	0.006	–	–	0.004	0.002	0.02	0.01
10	0.001	0.001	0.003	0.004	0.004	0.004	0.002	0.003	0.003	0.003	0.002	0.002	0.002	0.003
11	0.09	0.11	0.05	0.03	0.04	0.03	0.04	0.04	0.08	0.08	0.03	0.02	0.05	0.05
12	0.01	0.01	0.02	0.03	0.01	0.004	0.01	0.02	0.01	0.003	0.007	0.005	0.01	0.02
13	0.58	–	0.08	0.06	0.11	0.17	0.09	0.08	–	–	0.03	0.02	0.10	0.10
14	0.01	0.01	0.04	0.09	0.05	0.05	0.05	0.13	–	–	0.03	0.03	0.04	0.03
15	0.19	0.22	0.92	1.02	1.56	3.79	0.11	0.10	0.89	0.33	0.10	0.09	0.78	2.1
16	0.02	0.01	0.02	0.02	0.05	0.03	0.07	0.23	0.04	–	0.02	0.01	0.04	0.12

From Esmen *et al.* (1979a) (personal samples; 7–8-h sampling times; analysed by PCOM, using the equivalent of NIOSH A rules, combined with TEM) (Esmen et al., 1978)

[a] Forming: all hot-end workers, cupola operators, batch mixers, transfer operators and charging operators

[b] Production: cold-end workers in direct contact with fibres, but not involved in cutting, sawing, sanding or finishing operations

[c] Manufacturing: workers involved in general manufacturing operations such as trimming, sawing, cutting, finishing, painting finished boards and handling boxed and/or packaged goods

[d] Maintenance: maintenance workers who repair production machinery and do general work in the production area as needed, including sweeping floors and cleaning dust collectors and machinery

[e] Quality control: workers who sample products and ascertain product quality

[f] Shipping (transport of packaged material): fork-lift truck operators and shipping yard operators

Table 20. Summary statistics[a] for measures of exposure to respirable fibres, by plant, total fibre-glass-worker cohort, 1946–87[b,c]

Statistics	Plant										All plants
	1	2	4	5	6	9	10	11	14	15	
RFib-AIE (fibres/cm^3)											
Median	0.039	0.002	0.050	0.001	0.167	0.040	0.036	0.096	0.046	0.018	0.035
Mean	0.053	0.003	0.055	0.001	0.211	0.048	0.350	0.096	0.049	0.034	0.073
Coefficient of variation[d]	0.854	1.447	0.579	2.955	0.990	0.747	2.109	0.588	0.732	1.404	2.796
RFib-Cum (fibre/cm^3–months)											
Median	2.638	0.101	2.466	0.086	6.382	1.833	1.168	5.500	1.839	0.892	1.441
Mean	7.116	0.211	5.041	0.129	13.408	4.998	23.483	10.273	5.032	2.788	6.080
Coefficient of variation[d]	1.324	1.629	1.277	1.285	1.346	1.534	2.882	1.085	1.624	1.856	3.078

[a] Computed through December 31, 1987, over the entire work history, for exposed workers only

[b] RFib, respirable fibre; Cum, cumulative exposure; AIE, average intensity of exposure

[c] Marsh *et al.* (2001a)

[d] Coefficient of variation = standard deviation divided by mean

Table 21. Concentrations (fibre/cm^3) of total airborne fibres in dust zones of one rock (stone) wool and one slag wool production plant in the USA

Dust zone	No. of samples	Total fibres (fibre/cm^3)	
		Average	Range
Rock (stone) wool			
Warehouse	3	1.4	1.1–1.7
Mixing/Fourdrinier[a] ovens	3	0.14	0.13–0.18
Panel finishing	12	0.40	0.13–1.3
Fibre forming	10	0.20	0.07–0.65
Erection and repair	13	0.24	0.04–1.1
Tile finishing	22	0.31	0.10–0.74
All samples	63	0.34	0.04–1.7
Slag wool			
Maintenance	15	0.08	0.01–0.24
Block production	8	0.05	0.02–0.11
Blanket line	5	0.05	0.02–0.09
Boiler room	2	0.05	0.04–0.07
Yard	2	0.09	0.05–0.13
Ceramic block	7	0.42	0.11–0.95
Shipping	3	0.04	0.02–0.06
Main plant	11	0.01	0.006–0.58
Mould formation	19	0.03	0.005–0.08
All samples	72	0.10	0.005–0.95

From Corn *et al.* (1976) (personal samples; 8-h sampling times; analysed by PCOM, using the equivalent of NIOSH A rules, combined with TEM)

[a] Fourdrinier, a machine which forms wet board of approximately 50% fibre

of airborne fibres seen in these plants were due to the larger percentage of fibres with diameters < 3 μm compared to that in the glass fibre production operations surveyed.

Jacob *et al*. (1993) evaluated the concentrations of airborne fibres associated with several production operations in glass wool manufacturing plants in the USA. As indicated in Table 22, some variation in fibre concentrations was observed between the different operations, but the overall concentrations measured were low (i.e. < 0.20 fibre/cm^3) and the arithmetic mean concentration ranged from 0.022–0.29 fibre/cm^3 for the 14 manufacturing operations evaluated. Typically half or fewer of the airborne fibres counted were identified as glass fibres.

The North American Insulation Manufacturers' Association (NAIMA), an association of producers of glass fibre and rock (stone) and slag wool in the USA, recently published a large database of airborne fibre concentrations measured during manufacturing and installation operations during 1984–2000 (Marchant *et al*., 2002). The

Table 22. Arithmetic mean concentration of airborne fibres (fibre/cm^3) associated with various manufacturing operations involving glass wool insulation

	Total fibres[a]	Total glass fibres[b]	Respirable fibres[c]	Respirable glass fibres[d]
Equipment insulation fabrication[e]				
Arithmetic mean	0.026	0.009	0.007	0.001
95% confidence limits[f]	0.022–0.031	0.007–0.012	0.004–0.009	0.0004–0.002
95th percentile[f]	0.034	0.016	0.010	0.003
Number of samples	8	8	4	4
Moulding media				
Arithmetic mean	0.028	0.012	0.012	0.008
95% confidence limits	0.021–0.039	0.007–0.019	0.007–0.018	0.004–0.014
95th percentile	0.083	0.048	0.042	0.033
Number of samples	31	31	16	16
Fabrication, press operator, packer				
Arithmetic mean	0.20	0.14	0.087	0.071
95% confidence limits	0.17–0.23	0.11–0.17	0.072–0.102	0.059–0.083
95th percentile	0.32	0.24	0.12	0.11
Number of samples	24	24	12	12
Fabrication, other				
Arithmetic mean	0.038	0.015	0.007	0.002
95% confidence limits	0.028–0.051	0.011–0.020	0.005–0.009	0.0008–0.004
95th percentile	0.064	0.031	0.010	0.005
Number of samples	12	12	6	6
Metal building insulation[h]				
Arithmetic mean	0.043	0.017	0.017	0.009
95% confidence limits	0.038–0.049	0.014–0.020	0.014–0.022	0.006–0.012
95th percentile	0.076	0.032	0.028	0.018
Number of samples	31	31	16	16
Manufactured housing[i]				
Arithmetic mean	0.19	0.080	0.032	0.019
95% confidence limits	0.12–0.31	0.05–0.124	0.014–0.052	0.010–0.028
95th percentile	0.34	0.18	0.074	0.040
Number of samples	20	20	8	8
Pipe insulation				
Arithmetic mean	0.20	0.052	0.055	0.020
95% confidence limits	0.13–0.27	0.030–0.081	0.035–0.072	0.013–0.027
95th percentile	0.46	0.15	0.091	0.037
Number of samples	15	15	8	8
Range assembly				
Arithmetic mean	0.058	0.039	0.029	0.023
95% confidence limits	0.043–0.080	0.027–0.055	0.015–0.044	0.011–0.037
95th percentile	0.113	0.095	0.071	0.062
Number of samples	25	25	11	11

Table 22 (contd)

	Total fibres[a]	Total glass fibres[b]	Respirable fibres[c]	Respirable glass fibres[d]
Range assembly, wool unloader only				
Arithmetic mean	0.16	0.078	0.12	0.10
Values[j]	0.18, 0.13	0.083, 0.072		
Number of samples	2	2	1	1
Duct assembly				
Arithmetic mean	0.038	0.009	0.008	0.005
95% confidence limits	0.027–0.055	0.007–0.010	0.007–0.009	0.005–0.006
95th percentile	0.078	0.012	0.009	0.007
Number of samples	12	12	6	6
Duct board installation				
Arithmetic mean	0.022	0.002	0.006	0.002
95% confidence limits	0.019–0.026	0.001–0.002	0.004–0.007	0.001–0.003
95th percentile	0.042	0.006	0.009	0.005
Number of samples	29	29	15	15
Water heater assembly				
Arithmetic mean	0.047	0.030	0.022	0.018
95% confidence limits	0.034–0.058	0.022–0.040	0.013–0.034	0.010–0.028
95th percentile	0.074	0.054	0.044	0.036
Number of samples	11	11	6	6
Flex duct assembly				
Arithmetic mean	0.073	0.037	0.029	0.022
95% confidence limits	0.062–0.087	0.029–0.047	0.022–0.035	0.016–0.028
95th percentile	0.16	0.11	0.063	0.055
Number of samples	62	62	31	31
Removal of pipe and ceiling insulation				
Arithmetic mean	0.29	0.10	0.13	0.042
95% confidence limits	0.20–0.41	0.06–0.14	0.10–0.16	0.023–0.059
95th percentile	0.77	0.25	0.25	0.085
Number of samples	14	14	14	14

From Jacob *et al*. (1993) (personal and area samples; task weighted; analysed by NIOSH Method 7400 — A and B counting rules)

[a] Total fibres, NIOSH 7400 A rules, both filters and cowls

[b] Total glass fibres, NIOSH 7400 A rules, both filters and cowls, glass fibres only

[c] Respirable fibres, NIOSH 7400 B rules, filters and cowls

[d] Respirable glass fibres, NIOSH 7400 B rules, filters and cowls, glass fibres only

[e] A roll of light-density glass fibre insulation is fed through a coater that applies a facing and it is rolled up again.

[f] 95% confidence limits on the arithmetic mean

[g] 95th percentile of the data (95% of all measurements were less than this value)

[h] A roll of light-density glass fibre insulation is unrolled, sometimes cut into a thinner blanket, a coated facer is applied, and the insulation is rolled up again.

[i] Prefabricated housing

[j] When only two samples were measured, the measured values are presented.

database was established as a component of a voluntary workplace safety programme (designated the Health and Safety Partnership Program [HSPP]) developed by NAIMA after discussion with representatives from the US Occupational Safety and Health Administration (OSHA). These data, presented in Tables 23–26, demonstrate that the concentrations of airborne fibres measured during the production of glass and slag and/or rock (stone) wool are generally below 1 fibre/cm^3, which is a voluntary permissible 8-h time-weighted average (TWA) exposure limit, except in those areas where small-diameter fibres (< 1 µm in diameter) are produced (i.e. manufacture of aircraft insulation and separator and filtration media).

The concentrations of fibres measured during the production of refractory ceramic fibres in the USA were higher than those measured in glass wool and continuous glass filament plants, but were comparable with those measured in rock (stone) wool and slag wool production plants (Esmen *et al.*, 1979b). These data are presented in Table 27. Considerable variation in the concentrations of airborne fibres was noted between plants and within operations in individual plants. Approximately 90% of the airborne fibres in the three facilities evaluated were determined to be respirable (i.e. < 3 µm in diameter), as determined by PCOM and electron microscopy.

Additional monitoring of exposure to fibres was conducted in plants that produced refractory ceramic fibres in the USA from the late 1970s to the early 1990s (Corn *et al.*, 1992). However, much of this monitoring was sporadic, conducted by different consultants or institutions, focused on unit operations or processes of particular interest and emphasized monitoring of internal facilities rather than plants operated by secondary users. The estimates of exposure during the production of refractory ceramic fibres and related operations were discussed in detail by Rice *et al.* (1996, 1997).

The development of the unified Product Stewardship Program (PSP) by the industry trade association, the Refractory Ceramic Fiber Coalition (RCFC), in 1990 and the signing of a voluntary consent agreement with the US Environmental Protection Agency in 1993, brought greater conformity to methods for fibre sampling, counting and analysis of refractory ceramic fibres; more data were collected from consumers and end-users and increased emphasis was placed on random sampling. The data collected for this programme are presented in Table 28 (Maxim *et al.,* 1994, 1997, 1999a, 2000a).

These data demonstrate that exposure to refractory ceramic fibres varies widely from one functional job category to another. Most mean time-weighted average (TWA) concentrations of refractory ceramic fibres recorded during manufacture and processing operations are currently below the recommended exposure limit set by the US MMVF industry of 0.5 fibre/cm^3; higher mean TWA concentrations were measured during product finishing and removal operations (Maxim *et al.*, 1997). In addition, the analysis of industry data on a calendar time-period basis indicates that the average concentrations of airborne refractory ceramic fibres during manufacture and processing operations declined from 1.2 fibre/cm^3 in 1990 to less than 0.4 fibre/cm^3 in 2000 (Maxim *et al.*, 2000a).

Table 23. Glass wool manufacture: exposure to glass wool fibres (fibre/cm^3) by product type

Product type	Sample size	Exposure (fibre/cm^3)			
		Mean	Standard deviation	Median	Range
Air handling products	12	0.03	0.03	0.02	0.01–0.13
Aircraft insulation	67	0.19	0.36	0.06	0.01–2.29
Appliance insulation	28	0.12	0.29	0.03	0.01–1.30
Automotive insulation	102	0.02	0.03	0.01	0.01–0.18
Separator and filtration media	376	0.80	0.84	0.51	0.01–4.63
Blowing wool with binder	71	0.04	0.03	0.03	0.01–0.02
Blowing wool without binder	53	0.11	0.12	0.08	0.01–0.49
High density board	14	0.02	0.02	0.01	0.01–0.09
Pipe insulation	114	0.05	0.10	0.02	0.01–0.70
Insulation batts and blankets	472	0.05	0.09	0.02	0.01–0.97
Other[a]	339	0.07	0.18	0.02	0.01–2.30

From Marchant *et al.* (2002) (personal samples; > 90% of the samples in the database were collected and analysed by NIOSH method 7400 B counting rules; sampling times greater than 4 h)

[a] Includes acoustical panels and non–specified industrial and commercial products

Table 24. Glass wool manufacture: exposure to glass wool fibres (fibre/cm^3) by job description

Job description	Sample size	Exposure (fibre/cm^3)			
		Mean	Standard deviation	Median	Range
Scrap baler/compactor	29	0.05	0.05	0.04	0.01–0.25
Batch/binder mixer	40	0.18	0.33	0.04	0.01–1.30
Cutting/hot press mould	109	0.04	0.12	0.01	0.01–0.88
Forming	289	0.11	0.23	0.02	0.01–2.30
General labourer/maintenance	62	0.11	0.33	0.02	0.01–2.29
Packaging	890	0.34	0.67	0.04	0.01–4.63
Quality control/research	75	0.18	0.23	0.09	0.01–1.20
Sewing/laminating/assembly	91	0.08	0.11	0.03	0.01–0.62
Shipping/receiving	53	0.01	0.01	0.01	0.01–0.06
Other[a]	10	0.11	0.20	0.05	0.01–0.66

From Marchant *et al.* (2002) (personal samples; sampling times greater than 4 h; analysed by NIOSH method 7400 B counting rules)

[a] Includes administration and blowing wool chopper operator or nodulator

Table 25. Slag and/or rock (stone) wool manufacture and installation: exposure to wool fibres (fibre/cm^3) by product type

Product type	Sample size	Exposure (fibre/cm^3)			
		Mean	Standard deviation	Median	Range
Manufacturing					
Ceiling panel/tile	412	0.20	0.19	0.15	0.01–1.41
Other manufacturing[a]	17	0.06	0.04	0.05	0.01–0.15
Installation					
Ceiling panel/tile	33	0.23	0.21	0.17	0.02–0.82
Spray-on fire-proofing	15	0.08	0.10	0.05	0.02–0.42
Insulation batt and blanket	12	0.09	0.04	0.08	0.04–0.16
Other installation[a]	14	0.11	0.11	0.06	0.02–0.4

From Marchant *et al.* (2002) (personal samples; sampling times greater than 4 h; analysed by NIOSH method 7400, B counting rules)

[a] Includes air-handling products, appliance insulation, blowing wool with binder, cavity loose-fill insulation, pipe insulation and safety blanket and board.

Table 26. Slag and/or rock (stone) wool manufacture and installation: exposure to wool fibres (fibre/cm^3) by job description

Job description	Sample size	Exposure (fibre/cm^3)			
		Mean	Standard deviation	Median	Range
Manufacturing					
Supervisory	17	0.13	0.11	0.10	0.01–0.40
Forming	162	0.24	0.22	0.18	0.01–1.41
Maintenance	79	0.18	0.16	0.14	0.01–0.79
Packaging	62	0.25	0.20	0.23	0.01–1.00
Quality control	20	0.21	0.21	0.16	0.01–0.80
Shipping/receiving	55	0.14	0.14	0.08	0.01–0.57
Other manufacturing[a]	34	0.09	0.10	0.05	0.01–0.42
Installation					
Installers	65	0.16	0.17	0.10	0.02–0.82
Other installation[a]	9	0.09	0.12	0.05	0.02–0.40

From Marchant *et al.* (2002) (personal samples; sampling times greater than 4 h; analysed by NIOSH method 7400 B counting rules)

[a] Includes assembly, cutting and sawing with power tools, vehicle driver production, warehousing, feeder and general labourer.

Table 27. Total concentrations of airborne fibres and concentrations of respirable fibres in dust zones of three refractory ceramic fibre production plants in the USA

Dust zone	Total respirable fibres [a] (fibre/cm^3)	Total fibres[a] (fibre/cm^3)	Total fibres[b] (fibre/cm^3)	Respirable fraction[c]
Plant A (total suspended particulate matter)	2.6	3.3	2.6	0.79
Finishing	2.1	2.6	1.9	0.82
CVF	4.2	5.2	4.3	0.80
Lines 1 and 2	0.94	1.1	0.73	0.83
Lines 3 and 4	0.08	0.09	0.04	0.89
OEM	6.9	8.7	7.6	0.79
Maintenance	0.50	0.64	0.52	0.79
GFA	0.53	0.80	0.74	0.66
Shipping	0.27	0.34	0.22	0.78
Quality control	0.11	0.15	0.11	0.71
Plant B (total suspended particulate matter)	1.4	1.5	0.63	0.92
Textile	0.88	1.1	0.62	0.79
Maintenance	0.95	1.0	0.27	0.96
Furnace	1.5	1.6	0.60	0.96
Process	2.4	2.6	1.1	0.95
Quality control	0.62	0.68	0.33	0.92
Plant C (total suspended particulate matter)	0.21	0.23	0.05	0.91
Maintenance	0.12	0.12	0.01	0.98
Fiberizing	0.22	0.23	0.04	0.96
Felting	0.20	0.24	0.10	0.82
Pressing	0.23	0.26	0.08	0.89
Finishing	0.26	0.28	0.06	0.93
Fibre cleaning	0.06	0.07	0.01	0.94
Mixing	0.02	0.03	0.01	0.93
Shipping	0.04	0.05	0.03	0.84
Job centre	0.22	0.23	0.04	0.94

From Esmen *et al*. (1979b)

[a] As determined by both electron and optical microscopy, including fibres < 5 μm in diameter

[b] As determined by optical microscopy only

[c] Total concentration of respirable fibres/total concentration of fibres

CVF, mixing of bulk fibre with colloidal silica and vacuum formed; OEM, trimming of some products from CVF process with hand saws, drilling and packaging; GFA, cutting by hand of blankets from line 2 into specific shapes

Table 28. Concentrations (fibre/cm^3) of refractory ceramic fibres during manufacturing, processing and use in the USA (1993–96)

Functional job category	Data set	Fibre concentration (TWA) (fibre/cm^3)					
		Sample size	Minimum	Maximum	Arithmetic mean of sample	Median of sample	Standard deviation of sample
Assembly	Internal	207	0.005	2.2	0.30	0.22	0.31
	External	211	0.007	1.9	0.28	0.15	0.35
	Combined	418	0.005	2.2	0.29	0.19	0.35
Auxiliary	Internal	148	0.004	0.81	0.092	0.036	0.14
	External	157	0.002	2.7	0.20	0.082	0.39
	Combined	305	0.002	2.7	0.15	0.056	0.30
Fibre production	Internal	250	0.009	1.9	0.22	0.13	0.28
	External	None					
	Combined	NA					
Finishing	Internal	206	0.028	2.7	0.66	0.50	0.48
	External	375	0.009	30	0.99	0.40	2.3
	Combined	581	0.009	30	0.87	0.46	1.9
Installation	Internal	None					
	External	288	0.003	2.5	0.41	0.24	0.47
	Combined	NA					
Mixing and forming	Internal	231	0.007	1.4	0.30	0.20	0.28
	External	186	0.010	4.1	0.32	0.15	0.52
	Combined	417	0.007	4.1	0.31	0.18	0.40
Other (NEC)	Internal	96	0.008	0.90	0.11	0.048	0.14
	External	244	0.003	6.4	0.24	0.056	0.56
	Combined	340	0.003	6.4	0.20	0.054	0.48

Table 28 (contd)

Functional job category	Data set	Fibre concentration (TWA) (fibre/cm^3)					
		Sample size	Minimum	Maximum	Arithmetic mean of sample	Median of sample	Standard deviation of sample
Removal	Internal	5	0.66	3.2	1.6	1.20	0.88
	External	103	0.027	5.4	1.2	0.90	1.0
	Combined	108	0.027	5.4	1.2	0.91	1.0
Combined	Internal	1143	0.004	3.2	0.31	0.18	0.37
	External	1564	0.002	30	0.52	0.20	1.3
	Combined	2707	0.002	30	0.43	0.19	1.0

From Maxim *et al*. (1997) (‘internal’ samples collected from operations inside a plant manufacturing or processing refractory ceramic fibres; ‘external’ samples collected from other operations in which refractory ceramic fibres are processed or used)
NA, not applicable; NEC, not elsewhere classified

(ii) *Europe*

In the late 1970s, Head and Wagg (1980) studied airborne concentrations of both total particulate and respirable fibres in 25 manufacturing plants and construction sites in the United Kingdom. Various types of MMVF were evaluated including insulation wools (i.e. glass wool and rock (stone) and slag wool), continuous filament glass fibre, special-purpose fibres: glass microfibres (i.e. fibres with nominal mean diameters ranging from 0.1–3 μm) and refractory ceramic fibres.

Four plants that produced insulation wools were evaluated; one rock (stone) slag wool plant and three glass wool fibre manufacturing plants. The mean concentrations of respirable fibres were in the range 0.12–0.31 fibre/cm^3 in the glass wool fibre plants. A closer examination of these facilities found that the mean concentrations of airborne fibres were lower (i.e. 0.02–0.26 fibre/cm^3) in the basic production areas than in the areas where the fibres were fabricated into finished products, especially when machining operations were involved in the fabrication. The fabrication operations using rock (stone) or slag wool resulted in higher average concentrations of airborne respirable fibres (mean, 0.89; range, 0.03–10.3 fibres/cm^3) (see Table 29) (Head & Wagg, 1980).

For operations using continuous glass filament, principally the manufacture and weaving of textile yarns, the mean total fibre concentrations ranged from 0.006–0.28 fibre/cm^3. However, the overall mean concentrations of airborne respirable fibres were 0.02 fibre/cm^3 or below (Head & Wagg, 1980). The fibres in this group cover user processes only and for convenience have been subdivided into glass microfibres and high-quality aerospace insulation products.

In the manufacture of high efficiency filter paper, including filter production, and in the manufacture of high efficiency fabric type filters, total dust concentrations are characteristically low, the overall range of means being 0.4–1.4 mg/m^3, but with the potential for high respirable fibre counts, the range of overall mean concentrations being 0.8–3.70 fibres/cm^3 and the range of individual values being 0.02–18.83 fibres/cm^3. The maximum fibre count was found at a paper slitting machine (Head & Wagg, 1980).

From 1977–80, scientists from the Institute of Occupational Medicine in Edinburgh, United Kingdom, measured the concentrations of airborne fibres in 13 European plants, of which six produced rock (stone) wool (plants 1, 3, 4, 5, 8 and 9), four, glass wool (plants 2, 6, 7 and 10) and three, continuous glass filaments (plants E, J and N) (i.e. continuous glass filament or textile glass) (Ottery *et al.*, 1984). The data from this study were used as the basis for the exposure assessment component of the study by Saracci *et al.* (1984a,b; IARC, 1988). The workforce at each factory was classified into occupational groups on the basis of measured exposure levels and working areas, and some members of each group were selected at random for personal sampling. A total of 1078 samples were collected for counting of respirable fibres at the rock (stone) wool and glass wool plants, generally over a 7–8-h period. Upon re-analysis, the concentrations of respirable fibres originally reported were determined to be too low by a factor of about two (ranging between 1 and 2.8), and were therefore corrected (Cherrie *et al.*, 1986).

Table 29. Overall mean concentrations of total airborne dust and respirable fibres in insulation wool production plants in the United Kingdom (sampling period not stated)

Fibre type	Plant no.	Mean total dust			Mean respirable fibres[a]		
		No. of samples	Concentration (mg/m^3)	Range	No. of samples	Concentration (fibre/cm^3)	Range
Glass wool	Plant 1	32	11.1	0.7–78.2	50	0.31	0.02–1.10
Glass wool	Plant 2	16	4.1	0.5–14.3	35	0.27	0.01–0.79
Glass wool	Plant 3	30	8.9	0.4–51.3	67	0.12	0.003–0.85
Rock (stone)/slag wool	Plant 4	22	6.5	0.7–16.2	55	0.89	0.03–10.3

From Head & Wagg (1980)

[a] Respirable fibres are defined as being < 3 μm diameter and > 5 μm long.

Note: Overall mean values include both breathing-zone and static-sample results.

Tables 30 and 31 present the revised data from the glass wool and rock (stone) wool plants; only unrevised figures from the study by Ottery *et al.* (1984) are available for the three continuous glass filament plants, and these are presented in Table 32.

The range of group arithmetic mean fibre concentrations in the four glass wool plants was 0.01–1.00 fibre/cm^3. The highest concentrations were associated with the manufacture of special fine-fibre ear plugs. In the main production and secondary production groups, the concentrations ranged from 0.01–0.16 fibre/cm^3 (Cherrie *et al.*, 1986). In the rock (stone) wool plants, the combined arithmetic means for the occupational groups were 0.01–0.67 fibre/cm^3. The concentrations of respirable glass fibres measured in the continuous glass filament plants were very low; the occupational group means ranged from 0.001–0.023 fibre/cm^3 (Ottery *et al.*, 1984).

In two glass wool plants in France that were surveyed in the mid-1980s, the mean concentration of airborne fibres < 3 μm in diameter and > 5 μm in length was 0.05–0.18 fibre/cm^3 in different working zones (Kauffer & Vigneron, 1987).

An experimental simulation of a rock (stone) wool production process with conditions similar to those operating in the 1940s was carried out in a Danish pilot plant to determine the effect on concentrations of airborne fibres of the addition of oil to the rock (stone) wools. The addition of oil to the product resulted in a threefold to ninefold reduction in the concentration of airborne fibres in different situations. The TWA concentrations of respirable fibres were about 1.5 fibre/cm^3 when the product was treated with oil and 5.0 fibres/cm^3 in the absence of oil. No substantial differences in concentrations of airborne fibres were observed during the manufacture and handling of batch-produced rock (stone) wool and continuously produced rock (stone) wool (Cherrie *et al.*, 1987).

A survey of the occupational environment of 10 rock (stone) wool and glass wool production plants was conducted by the MMVF industry and the Swedish Work Environment Fund. The products evaluated included insulation rock (stone) and glass wools, continuous glass filament and special-purpose products (earplugs (glass wool) and Inorphil (rock wool)). A pilot study at the factory that produced continuous glass filaments showed that no airborne respirable glass fibres were present, and this factory was therefore excluded from further epidemiological investigation. From the remaining nine factories, 1350 samples were collected. In insulation wool production, the arithmetic mean exposure to total dust and respirable fibres as assessed by gravimetric analysis and PCOM, respectively, are presented in Table 33. The mean concentrations of respirable fibres to which workers were exposed ranged from 0.15–0.27 fibre/cm^3 for rock (stone) wool production workers and 0.14–0.23 fibre/cm^3 for glass wool production workers; maintenance and cleaning workers were found to be exposed to higher concentrations of fibres than process workers. During the production of special-purpose fibres (Table 34), production workers were exposed to higher concentrations of respirable fibres (i.e. 1.4 fibre/cm^3 for rock (stone) wool and 0.62 fibre/cm^3 for glass wool) than in production of insulation wool (0.15 and 0.14 fibre/cm^3, respectively). The

Table 30. Concentrations of respirable fibres (fibre/cm^3)[a] in combined occupational groups and total concentration of airborne dust in mg/m^3 in four European glass wool plants (1977–80)

Combined occupational group	Plant 2			Plant 6			Plant 7			Plant 10		
	No.[b]	Mean[c]	Range	No.[b]	Mean[c]	Range	No.[b]	Mean[c]	Range	No.[b]	Mean[c]	Range
Respirable fibre concentrations												
Preproduction	8	0.01	< 0.01–0.01	5	0.01	0.01	5	0.01	0.01–0.02	5	0.01	< 0.01–0.03
Production	26	0.01	< 0.01–0.03	27	0.03	0.01–0.11	39	0.05	0.01–0.62	61	0.05	< 0.01–0.22
Maintenance	4	0.03	0.01–0.06	12	0.04	< 0.01–0.17	20	0.07	0.01–0.60	27	0.02	< 0.01–0.06
General	10	0.02	0.01–0.04	10	0.02	0.01–0.04	15	0.03	0.01–0.06	12	0.03	< 0.01–0.06
Secondary process 1	32	0.05	0.01–0.21	26	0.03	< 0.01–0.07	37	0.04	0.01–0.11	36	0.02	< 0.01–0.06
Secondary process 2	–			2	0.07	0.05–0.09	23	1.00	0.17–4.02	45	0.16	0.02–1.39
Cleaning	–			4	0.01	0.01–0.02	–					
Airborne dust concentration												
Plant mean and range (mg/m^3)[d,e]	69	[0.6]		79	[1.3]		124	[1.0]		168	[1.3]	

From Cherrie *et al.* (1986) (personal samples; sampling times 2–7 h; analysed by PCOM)

[a] Including fibres < 3 μm in diameter

[b] Number of measurements

[c] Arithmetic mean, revised in 1986, compared to values of Ottery *et al.* (1984)

[d] From Ottery *et al.* (1984)

[e] Overall mean [calculated by the Working Group]

Table 31. Concentrations of respirable fibres (fibre/cm^3)[a] in combined occupational groups and total concentration of airborne dust (mg/m^3) in six European rock (stone) wool plants (1977–80)

Combined occupational group	Plant 1			Plant 3			Plant 4			Plant 5			Plant 8			Plant 9		
	No.[b]	Mean[c]	Range	No.[b]	Mean[c]	Range	No.[b]	Mean[c]	Range	No.[b]	Mean[c]	Range	No.[b]	Mean[c]	Range	No.[b]	Mean[c]	Range
Respirable dust concentration																		
Preproduction	8	0.08	0.01–0.22	3	0.06	0.03–0.11	7	0.03	0.01–0.07	2	0.01	0.01	1	0.04	0.04	4	0.01	< 0.01–0.01
Production	36	0.10	0.02–0.37	28	0.12	0.03–0.32	27	0.06	0.02–0.19	22	0.06	0.02–0.14	19	0.05	0.01–0.13	51	0.05	0.01–0.16
Maintenance	9	0.08	0.05–0.18	8	0.05	0.03–0.10	20	0.05	0.02–0.12	12	0.05	0.01–0.14	9	0.03	0.01–0.07	10	0.04	0.01–0.11
General	16	0.08	0.02–0.37	8	0.07	0.04–0.14	13	0.06	0.02–0.09	7	0.04	0.03–0.07	2	0.04	0.04	23	0.06	0.01–0.36
Secondary process 1	32	0.10	0.03–0.21	11	0.12	0.06–0.23	28	0.08	0.03–0.33	16	0.07	0.01–0.15	24	0.08	0.01–0.20	55	0.06	0.02–0.39
Secondary process 2	11	0.40	0.09–1.40	3	0.34	0.25–0.41	–			–			3	0.25	0.19–0.36	22	0.67	0.06–1.37
Cleaning	–			4	0.13	0.05–0.29	8	0.06	0.02–0.14	5	0.09	0.04–0.11	8	0.09	0.01–0.18	12	0.14	0.02–0.44
Airborne dust concentration																		
Plant mean and range (mg/m^3)[d,e]	101	[2.4]		56	[1.6]		86	[1.1]		53	[1.0]		60	[1.0]		164	[0.7]	

From Cherrie *et al.* (1986) (personal samples; sampling times 2–7 h; analysed by PCOM)

[a] Including fibres < 3 µm in diameter

[b] Number of measurements

[c] Arithmetic means, revised in 1986, compared to values of Ottery *et al.* (1984)

[d] From Ottery *et al.* (1984)

[e] Overall mean [calculated by the Working Group]

Table 32. Concentrations of respirable fibres (fibre/cm^3)[a] in combined occupational groups and total concentrations of airborne dust (mg/m^3) at three European continuous filament glass fibre plants (1977–80)

Combined occupational group	Plant E			Plant J			Plant N		
	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range
Respirable fibre concentrations									
Preproduction	12	0.004	0.001–0.015	–			6	0.009	0.005–0.017
Production I	54	0.002	0.001–0.012	19	0.001	0.001–0.003	44	0.007	0.001–0.039
Production II	–			32	0.001	0.001–0.003	22	0.023	0.005–0.112
Maintenance	16	0.005	0.001–0.022	–			15	0.014	0.006–0.023
General	2	0.005	–	11	0.001	0.001–0.003	7	0.012	0.008–0.020
Secondary process 1	70	0.002	0.001–0.016	87	0.002	0.001–0.006	27	0.007	0.005–0.017
Secondary process 2	–			–			6	0.022	0.006–0.056
Research and development	10	0.002	0.001–0.003	–					
Total airborne dust concentration									
Plant mean and range (mg/m^3)[a]	145	[1.5]		132	[0.61]		115	[0.9]	

From Ottery *et al*. (1984)

[a] Overall mean [calculated by the Working Group]

Table 33. Total concentrations of dust and respirable fibres during the production of insulation wool

Occupational group	Mean total dust (mg/m^3)		Mean respirable fibre concentration (fibre/cm^3)	
	Rock (stone) wool	Glass wool	Rock (stone) wool	Glass wool
Process workers	0.8	0.7	0.15	0.14
Maintenance workers	1.1	4.4	0.20	0.23
Cleaning workers	2.9	0.2	0.27	0.15
Mean (all groups)[a]	1.4	1.9	0.20	0.18
Total range	0.1–32	0.1–410	0.01–2.6	0.01–1.8

From Krantz (1988)

[a] Also includes handling of raw material

Table 34. Total concentrations of dust and respirable fibres during the production of special-purpose fibres

Occupational group	Total dust (mg/m^3)		Respirable fibre concentration (fibre/cm^3)	
	Rock (stone) wool	Glass wool	Rock (stone) wool	Glass wool
Process workers	2.0	0.6	1.4	0.62
Maintenance workers	–	0.4	–	0.20
Cleaning workers	–	0.4	–	0.16
Mean (all groups)[a]	2.0	1.0	1.4	0.47
Total range	0.5–2.0	0.1–1.4	0.45–1.9	0.08–2.4

From Krantz (1988)

[a] Also includes handling of raw material

main reason for these higher values was the absence of dust-reducing oil and binder in the special-purpose fibres together with manual handling (Krantz, 1988).

Plato *et al.* (1995b) used the data from this study as well as additional information on employee job titles, work tasks and periods of employment to develop a multiplicative model to assess past exposure to respirable fibres in rock (stone) wool and slag wool production workers in Sweden from 1938–90. This model took into account process changes, as well as the addition of binders and oil, and suggested that the levels of exposure in the MMVF industry had changed considerably during this period. The estimated average concentrations of airborne fibres during the 1940s were in the range 0.78–1.32 fibre/cm^3 which was between 16 and 26 times higher than the concentrations of airborne fibres measured in the 1980s.

Plato *et al*. (1995a) also evaluated exposure to MMVFs at 11 Swedish plants that manufactured prefabricated wooden houses. All the samples were analysed by PCOM as well as using a modified fibre-counting method specifically developed for this study. The alternative counting method was designed to exclude fibres other than MMVFs. The geometric mean of the concentration of airborne fibres to which insulators were exposed was 0.10 fibre/cm^3 (range, 0.03–0.30 fibre/cm^3) using the standard fibre-counting method, and 0.029 fibre/cm^3 (range, 0.013–0.077 fibre/cm^3) using the modified fibre-counting method. The results of the modified fibre-counting method were validated by SEM.

The concentrations of airborne fibres were also measured in three plants that produced rock (stone) wool insulation materials by personal sampling according to VDI 3492 (Tiesler *et al.*, 1993). The highest fibre concentration measured was 0.44 fibre/cm^3 and concentrations higher than 0.1 fibre/cm^3 were measured in only nine samples of a total of 69 (Draeger & Löffler, 1991). The German Ministry of Labour also published in its regulations for dangerous materials (TRGS 901) a summary of 192 measurements made during the production of glass and rock (stone) wool insulation materials. The 75th percentile of all these measurements of concentration of airborne fibres was 0.095 fibre/cm^3 and the 90th percentile was 0.25 fibre/cm^3. The concentrations of airborne fibres measured during insulation work with glass and rock (stone) wool products (102 samples) were: 75th percentile, 0.11 fibre/cm^3; 90th percentile, 0.40 fibre/cm^3 (TRGS, 1999).

For operations involving the manufacture and fabrication of refractory ceramic fibres, the overall mean concentration of airborne respirable fibres in a production plant was 1.27 fibre/cm^3 (range, 0.06–6.14 fibres/cm^3). The concentrations of airborne fibres during the manufacture and handling of refractory ceramic fibres in another plant were usually lower (mean, 0.44 fibre/cm^3; range, 0.09–0.87 fibre/cm^3). Airborne refractory ceramic fibres were also found to yield a proportion of fibres generally with the same length as glass wool and rock (stone) and slag wool fibres (Head & Wagg, 1980).

The exposure of workers to total dust and airborne fibres during the production and use of products made from refractory ceramic fibres was evaluated in the United Kingdom in the mid-1980s. The products studied included blankets, felts, yarns, papers, vacuum-formed shapes and boards. The data collected were pooled with the data that had been collected during previous surveys of similar operations by the United Kingdom Health and Safety Executive to yield comprehensive results. Fibre concentrations rarely exceeded 1.0 fibre/cm^3 (Friar & Phillips, 1989).

In the mid-1980s, the European manufacturers of refractory ceramic fibres and their products, collectively known as the European Ceramic Fibre Industries Association (ECFIA), developed a product stewardship programme, designated Control and Reduce Exposure (CARE), to monitor and control exposure to airborne fibres associated with their products. Several hundred TWAs were collected from sites of manufacture and end-use and the results were reported at both public forums and in the published literature (Burley *et al.*, 1997; Maxim *et al.*, 1998). The results of this programme are essentially similar to those obtained at plants making and using refractory ceramic fibres in the USA (see Table 29). The TWA concentrations of refractory ceramic fibres varied widely from one functional job category to another, both within and between plants. The analyses indicated that approximately 50% of TWA concentrations measured in the workplace are below 0.25 fibre/cm^3, 71% are below 0.5 fibre/cm^3, 84% are below 1 fibre/cm^3 and 94% are below 2 fibres/cm^3 (Maxim *et al.*, 1998).

Exposure to refractory ceramic fibres and AES wools during manufacturing and oven insulation operations was recently evaluated by Class *et al.* (2001). Monitoring was performed and fibre concentrations were determined using the WHO criteria. The mean concentrations of refractory ceramic fibres ranged from 0.07–0.39 fibre/cm^3 during manufacturing operations and the mean concentrations of AES wools ranged from 0.06–0.39 fibre/cm^3 during the same operations. The mean concentration of refractory ceramic fibres measured during oven insulation was 0.46 fibre/cm^3, whereas for AES wool, the mean concentration of fibres was 0.36 fibre/cm^3. From these data, the authors concluded that there was essentially no difference between the atmospheric concentrations of fibres produced by refractory ceramic fibres and AES wool during their production and end-use.

Exposure to airborne refractory ceramic fibres and total dust was also evaluated in plants producing aluminosilicate fibres in Poland. The mean concentrations of respirable refractory ceramic fibres ranged from 0.14–1.13 fibre/cm^3 and the mean concentrations of total dust ranged from 0.4–13.6 mg/m^3 (Wojtczak, 1994). In one plant that produced fibre blankets and mats, the mean concentrations of respirable refractory ceramic fibres ranged from 0.07–0.37 fibre/cm^3 while the concentrations of dust ranged from 0.4–2.9 mg/m^3 (Wojtczak *et al.,* 1996). In a plant that manufactured packing cord, insulating tape and paperboard products, the mean concentrations of respirable refractory ceramic fibres ranged from 0.05–0.62 fibre/cm^3, while the concentrations of dust were between 0.6 and 23.2 mg/m^3 (Wojtczak *et al.*, 1997).

(iii) *Other studies*

In 1990, the National Occupational Health and Safety Commission (NOHSC) of Australia specified the National Standard for Synthetic Mineral Fibres and Code of Practice for the Safe Use of Synthetic Mineral Fibres based on the recommendations of an expert working group. A survey of Australian plants manufacturing glass wool, rock (stone) wool and refractory ceramic fibres and user industries was undertaken from 1991–92 to measure the typical levels of exposure to airborne fibres and to monitor adherence to recommended work practices. A total of 1572 samples of both respirable fibres and inspirable dust were collected from more than 250 jobs or processes. The data from this survey are presented in Table 35. Nearly all (i.e. 1225 or 97.7%) of the

Table 35. Exposure to respirable fibres in the MMVF manufacturing industry in Australia

Type of MMVF	Job or process	Typical fibre count before introduction of NOHSC standard (fibre/cm^3)	Sample type	Count of respirable fibres after introduction of NOHSC standard (fibre/cm^3)			
				No.	Range	Geometric mean	Geometric standard deviation
Glass wool	Furnace operator	< 0.02		4	< 0.01–0.08	0.02	2.39
	Bulk production line	< 00.1–0.2		18	< 0.01–0.10	0.03	1.86
	Forming of specific shape	–		41	< 0.01–0.10	0.02	1.94
	Supervisor	< 0.02		6	< 0.03–0.10	0.04	1.63
	Packer	0.02–0.2		21	< 0.02–0.20	0.04	2.13
	Others	–		4	< 0.02–0.10	0.05	2.00
	All processes		Personal	49	< 0.01–0.20	0.04	1.83
			Static	45	< 0.01–0.10	0.02	2.04
			Total	94	< 0.01–0.20	0.03	2.06
Rock (stone) wool	Furnace operator	< 0.1–0.2	Personal	2	0.04–0.10	0.06	1.91
	Bulk production line	–	Personal	5	0.05–0.07	0.06	1.16
	Forming of specific shape	–	Personal	10	< 0.02–0.08	0.04	1.76
	Packer	0.03–0.4	Personal	7	< 0.02–0.10	0.03	1.89
	Cleaning and maintenance	–	Personal	6	< 0.02–0.20	0.08	2.17
	Supervisor	0.1–0.2		–	–	–	–
	All processes		Total	30	< 0.02–0.20	0.05	1.90
Refractory ceramic fibres	Furnace operator	–		4	0.04–0.4	0.15	2.88
	Bulk production line	< 0.05–1.3		4	0.20–0.9	0.42	1.97
	Forming of specific shape	–		31	0.02–2.0	0.34	3.15
	Others	–		3	0.09–2.0	0.38	4.78
	All processes		Personal	27	0.03–2.0	0.38	2.81
			Static	15	0.02–2.0	0.25	3.55
			Total	42	0.02–2.0	0.32	3.09

From Yeung & Rogers (1996)

reported fibre counts were below the established exposure standard of 0.5 fibre/cm^3 (Yeung & Rogers, 1996).

The levels of exposure to airborne refractory ceramic fibres were measured at two factories in Japan. In each factory, one manufacturing and one processing workplace were selected so that a total of four sampling sites were evaluated. Manufacturing site A produced pipes and tubes from refractory ceramic fibres. The workers at manufacturing site B were engaged in the cutting, binding and packaging of fibre blankets. Stationary and personal samples were collected, and analysed using PCOM. The geometric mean concentrations of airborne fibres were 0.10, 0.27, 0.30 and 0.66 fibre/cm^3 for workplace A manufacturing, A processing, B manufacturing and B processing, respectively. The results obtained from personal samples (range, 0.09–3.69 fibres/cm^3) were generally higher than those from stationary samples (range, 0.06–0.86 fibre/cm^3) (Hori *et al.*, 1993).

(*b*) *Exposure to compounds other than MMVFs in production plants*

The assessments of exposure conducted in conjunction with the epidemiological studies of MMVF workers (discussed more fully in section 2) have revealed a number of other substances to which workers in the production environment are exposed. The earlier estimates of these other sources of exposure in production operations were qualitative due to the limited details in the records available. However, methods for the quantitative estimation of exposure to various chemical substances and physical agents present in the workplace, in addition to airborne fibres, have been developed recently using the process of environmental reconstruction.

For example, in several of the plants included in the study of European MMVF workers (Saracci *et al.*, 1984a,b; Simonato *et al.*, 1986a,b, 1987; Boffetta *et al.,* 1992, 1997, 1999), asbestos gloves and aprons were worn by a few individuals for personal protection and as thermal insulation. In four factories, asbestos was used as stitching yarn and cloth. In at least one plant, olivine sand, potentially contaminated with a natural mineral fibre with a composition similar to tremolite asbestos, was also used (Cherrie & Dodgson, 1986).

Exposure to polycyclic aromatic hydrocarbons (PAHs) may have occurred close to the cupola furnaces in three rock (stone) wool plants and one glass wool plant and in one plant in which an electric furnace was used. The possibility of exposure to arsenic from copper slags in one factory was also suggested (Cherrie & Dodgson, 1986). In addition, in one plant included in this study, located in Germany, exposure to coal-tar, bitumen, quartz and asbestos was identified, but not quantified (Grimm, 1983; Grimm *et al.*, 2000). Confirmation that workers in the 1940s were exposed to PAHs, to heavy metals (i.e. zinc and lead) and to carbon monoxide at a Danish slag wool production factory has been obtained from a simulation study (Fallentin & Kamstrup, 1993).

A case–control study of lung cancer nested in the rock (stone) and slag wool component of the European cohort of MMVF production workers presented analyses based upon various indicators of exposure to asbestos, PAHs, crystalline silica, welding fumes, heavy metals (i.e. arsenic, cadmium, chromium and nickel), formaldehyde, diesel exhaust, paints and ionizing radiation (Kjaerheim *et al.*, 2002). These analyses were based on a new method for the subjective assessment of exposure in the 13 plants included in the study over time (Cherrie & Schneider, 1999).

The main epidemiological study of MMVF production workers in the USA (Enterline *et al.*, 1983; Enterline & Marsh, 1984; Enterline *et al.*, 1987; Marsh *et al.*, 1990, 1996, 2001a,b,c), in addition to reporting concentrations of airborne fibres, provided estimates of exposure to chemical substances and physical agents, including several potential carcinogens. Quantitative estimates of exposure to respirable fibres, asbestos, formaldehyde and silica, together with qualitative estimates of exposure to arsenic, asphalts, PAHs, phenolics, radiation and urea were presented in the update of a study on a cohort of 3035 rock (stone) wool and slag wool workers (Marsh *et al.*, 1996). Quantitative estimates of exposure to respirable fibres, formaldehyde and silica, and qualitative estimates for arsenic, asbestos, asphalt, epoxy, PAHs, phenolics, styrene and urea were presented in the update of the US cohort study of 32 110 glass fibre workers (Marsh *et al.*, 2001a). All the exposure estimates were derived from an extensive reconstruction of historical exposure in the 15 plants included in the study (Quinn *et al.*, 2001; Smith *et al.*, 2001).

Quantitative estimates of exposure to several chemical substances, in addition to respirable fibres, were also included in two case–control studies of malignant and non-malignant respiratory disease among employees of the oldest and largest glass fibre manufacturing plant in the USA (Chiazze *et al.*, 1992, 1993), and in a historical cohort mortality study of a continuous glass filament plant in the USA (Chiazze *et al.*, 1997; Watkins *et al.*, 1997). Using a reconstruction of the historical environment of these two plants, quantitative estimates of cumulative exposure to respirable fibres, asbestos, talc, formaldehyde, respirable silica, asphalt fumes and total particulate matter were generated for the glass fibre plant and quantitative estimates of cumulative exposure to respirable fibres, asbestos, refractory ceramic fibres, respirable silica, formaldehyde, total particulate matter, arsenic and total chrome (chromium oxides) were developed for the continuous glass filament plant. These estimates were then incorporated into a conditional logistic regression analysis of lung cancer and non-malignant respiratory disease in the workers at the two plants.

(*c*) *Exposure of workers during the installation and removal of MMVF insulation products*

Occupational exposure to MMVFs outside production facilities occurs when workers either install materials containing MMVFs or remove (old) MMVFs from their site of installation. Most of the data that have been collected are for MMVF installation although higher levels of exposure have been recorded during removal operations (Jacob *et al.*, 1993; Maxim *et al.*, 1997; Yeung & Rogers, 1996). Moreover, during removal operations, workers are also exposed to many other airborne particles, both fibrous and non-fibrous.

The exposure of insulation workers to airborne MMVFs has been the subject of investigation for some time. Fowler *et al.* (1971) surveyed individuals while they were installing various types of glass fibre insulation in the western USA in the early 1970s (see Table 36). The concentrations of fibres to which the installers were exposed ranged from 0.5–8.0 fibres/cm^3 with a median of 1.26 fibre/cm^3 and a mean of 1.8 fibre/cm^3.

The exposure of workers to MMVFs during the installation of several types of insulation in commercial and residential buildings and at two aircraft installation facilities in the USA was evaluated by Esmen *et al.* (1982). Detailed data from this survey are presented in Table 37. The average exposure of workers for all applications, except the blowing of thermal insulation into attics and operations involved in the fabrication of aircraft insulation, was reported to be in the range of 0.003–0.13 fibre/cm^3. The reported average concentration of fibres during the blowing operations was 1.8–4.2 fibres/cm^3 with measurements in the different operations in the range of 0.50–14.8 fibres/cm^3 and the mean fibre concentration during fabrication of aircraft insulation was in the range of 0.05–1.7 fibre/cm^3 with individual measurements ranging from 0.01–3.78 fibres/cm^3. The fibre concentrations to which installers, with the exception of blowing wool applications, were exposed were deemed to be similar to the concentrations of airborne fibres found in MMVF production operations.

Large surveys of the exposure of installers and end-users of MMVF insulation products to airborne fibres and total dust were conducted in the United Kingdom and Scandinavia from the late 1970s until the mid-1980s (Schneider, 1979a; Head & Wagg, 1980; Hallin, 1981; Schneider, 1984). Full-shift samples were not collected during these surveys (except by Hallin, 1981), but the sampling time was determined to be representative of the particular product or operation being evaluated. Since the equipment used to collect dust samples varied from site to site the results for total dust concentration can only be compared qualitatively between these surveys. The results from the surveys in Sweden and Denmark are presented in Tables 38 and 39, and those from the surveys conducted in the United Kingdom in Table 40.

The distribution of results for the concentrations of respirable fibres had geometric means of 0.22 and 0.14 fibre/cm^3 and geometric standard deviations of 3.3 and 3.8 in the Swedish and Danish surveys, respectively. Very few measurements exceeded 2.0 fibres/cm^3. The geometric mean concentration of respirable fibres was 0.046 fibre/cm^3 (standard deviation, 1.8) in open and well-ventilated spaces and 0.50 fibre/cm^3 (standard deviation, 3.1) in confined and poorly ventilated spaces (Schneider, 1979a; Schneider, 1984). In the survey of exposure during installation of insulation in the United Kingdom, the application of loose fill appeared to generate the highest concentration of respirable fibres (Head & Wagg, 1980).

From 1980–83, the United Kingdom Factories Inspectorate (1987) surveyed factories where MMVFs with a nominal diameter of < 3 μm were used. The concentrations of total dust and airborne fibres measured are shown in Table 41.

The arithmetic mean value of fibre concentrations (as defined by WHO) (see section 1.1.3), determined in nine randomly selected building sites in Europe (where

Table 36. Concentrations and dimensions of airborne fibres measured during various operations using glass fibre insulation

Operation	Parent material (range of mean[a] fibre diameters, µm)	No. of samples	Breathing zone samples	
			Mean fibre concentration (fibres/cm^3)	Range of mean fibre diameters (µm)
Duct wrapping	4.0–7.5	9	1.2	2.3–6.2
Wall and plenum insulation	7.2–10.2	4	4.0	3.5–8.4
Pipe insulation	5.6–8.5	3	0.7	3.1–4.1
Fan-housing insulation	6.9	1	1.6	3.5

From Fowler *et al.* (1971) (personal samples; sampling times 20–60 min; analysed by PCOM)
[a] Not length-weighted

Table 37. Airborne concentrations of respirable fibres[a] in the final preparation and installation of MMVF insulation, as determined by a combination of phase-contrast and electron microscopy

Product and job classification	No. of samples	Fibre concentration		
		Average (fibre/cm^3)	Range (fibre/cm^3)	Average respirable fraction[b]
Acoustical ceiling installer	12	0.003	0–0.006	0.55
Duct installation				
Pipe covering	31	0.06	0.007–0.38	0.82
Blanket insulation	8	0.05	0.025–0.14	0.71
Wrap around	11	0.06	0.03–0.15	0.77
Attic insulation				
Glass fibre				
Roofer	6	0.31	0.07–0.93	0.91
Blower	16	1.8	0.67–4.8	0.44
Feeder	18	0.70	0.06–1.48	0.92
Rock (stone)/slag wool				
Helper	9	0.53	0.04–2.03	0.71
Blower	23	4.2	0.50–14.8	0.48
Feeder	9	1.4	0.26–4.4	0.74
Building insulation installer	31	0.13	0.013–0.41	0.91

Table 37 (contd)

Product and job classification	No. of samples	Fibre concentration		
		Average (fibre/cm^3)	Range (fibre/cm^3)	Average respirable fraction[b]
Aircraft insulation				
Plant A				
Sewer	16	0.44	0.11–1.05	0.98
Cutter	8	0.25	0.05–0.58	0.98
Cementer	9	0.30	0.18–0.58	0.94
Others	7	0.24	0.03–0.31	0.99
Plant B				
Sewer	8	0.18	0.05–0.26	0.96
Cutter	4	1.7	0.18–3.78	0.99
Cementer	1	0.12	–	0.93
Others	3	0.05	0.012–0.076	0.94
Glass fibre duct				
Duct fabricator	4	0.02	0.006–0.05	0.66
Sheet–metal worker	8	0.02	0.005–0.05	0.65
Duct installer	5	0.01	0.006–0.20	0.87

From Esmen *et al.* (1982) (average concentration of fibres/cm^3 is equal to concentrations derived from both PCOM and electron microscopy; total fibre concentration was not included in the table for calculation of the average respirable fraction (respirable/total); results cannot be directly compared to results obtained by PCOM only; when counting and sizing by electron microscopy, only fibres of diameter ≤ 1 µm were treated.

[a] < 3 µm in diameter

[b] Arithmetic mean of respirable fibre concentration/total fibre concentration

glass and rock (stone) wool insulation materials were used in different manners) was reported to be 0.04 fibre/cm^3. This mean value was based on 22 stationary samples; measurements were made using the VDI 3492 method (electron microscopy with EDXA). The maximum concentration reported was 0.2 fibre/cm^3. When personal sample measurements were analysed, the mean product fibre concentration was 0.07 fibre/cm^3 and the maximum value was 0.45 fibre/cm^3. The glass and rock (stone) wool insulation materials were found to contribute about one-third of the total mineral fibre measured; one-third was attributed to gypsum fibres and the remaining one-third to other inorganic fibres (Tiesler *et al.*, 1990).

In a survey of the installation of insulation materials at industrial sites in the European chemical industry (outdoors) and in shipyards (indoors), 22 personal sampling measurements were made using the VDI 3492 method. The concentrations of

Table 38. Concentrations of total dust and respirable fibres[a] during installation of insulation in Sweden (1979–80)

Operation	Total dust (mg/m^3)		Respirable fibres (fibre/cm^3)	
	Mean[b]	Range	Mean[b]	Range
Attic insulation, existing buildings	11.6	1.7–21.7	1.11	0.1–1.9
Insulation of new buildings	2.63	0.5–11.1	0.57	0.07–1.8
Technical insulation	3.14	0.4–25	0.37	< 0.01–1.39
Acoustical insulation	1.8	1.7–1.9	0.15	0.11–0.18
Spraying	13.5	1.3–43.7	0.51	0.13–1.1
Hanging of fabric	4.18	3.6–5.2	0.60	0.30–0.76

From Hallin (1981)

[a] < 3 μm in diameter

[b] Calculated by the previous IARC Working Group (IARC, 1988)

Table 39. Concentrations of total dust and respirable fibres[a] during installation of insulation in Denmark

Operation	Total dust (mg/m^3)		Respirable fibres (fibre/cm^3)	
	Mean	Range	Mean	Range
Attic insulation, existing buildings	26.8	1.5–134	0.89	0.04–3.5
Insulation of new buildings	12.6	0.22–44	0.10	0.04–0.17
Technical insulation	7.1	1.8–12.8	0.35	0.03–1.6
Application in industrial products	0.88	0.83–0.91	0.05	0.01–0.11
Hot–house substrate	3.00	0.61–3.9	0.06	0.03–0.09

From Schneider (1984)

[a] ≤ 3 μm in diameter

WHO product fibres were between 0.003 and 0.29 fibre/cm^3, and the arithmetic mean was 0.10 fibre/cm^3. The concentrations of WHO product fibres during disassembly work at the same sites were also analysed. The mean value of 12 personal sample measurements was 0.32 fibre/cm^3 (range, 0.05–0.77 fibre/cm^3) (Julier *et al.*, 1993).

Insulation materials made of rock (stone) and glass wool are regularly removed and replaced in European power plants. The concentrations of inorganic fibres, excluding asbestos and gypsum, during these procedures (calculated from personal measurements) were reported to range between 0.21 and 0.99 fibre/cm^3 (Böckler *et al.*, 1995).

Table 40. Concentrations of total dust and respirable fibres[a] in breathing zone and static samples taken during installation of insulation and application of MMVFs in the United Kingdom

Product, use or process	Total dust (mg/m^3)				Respirable fibres (fibre/cm^3)	
	No. of samples	Mean	Range	No. of samples	Mean	Range
Construction insulation (glass fibre)						
Blankets	9	35.5	8.2–90	12	0.75	0.24–1.76
Loose fill	4	30.9	5.0–59.7	6	8.19	0.54–20.9
Fire protection (mineral wool)	9	17.2	1.9–51.5	22	0.77	0.16–2.57
Industrial product insulation (one plant)	4	0.8	0.6–1.0	12	0.10	0.02–0.36
Manufacture and use of high–temperature insulation and mouldings (refractory ceramic fibres)	6	1.7	0.7–5.2	11	0.48	0.09–0.87
Manufacture of stack block insulation and engine silencer insulation (refractory ceramic fibres)	11	9.8	1.5–22.9	30	2.2	0.35–5.64

From Head &Wagg (1980) (personal and area samples; sampling times at least 4 h; analysed by PCOM)

[a] ≤ 3 µm in diameter

Table 41. Concentrations of total dust and respirable fibres[a] during the manufacture and use of special-purpose fibres and refractory ceramic fibres

Process	Mean concentration of total dust (mg/m^3)	Total fibres/cm^3 (mean counts)[b]
Manufacture of glass fibre paper	0.47–2.28	2.9–1.3
Conversion of glass fibre paper	0.17–0.49	0.53–15.1
Manufacture of refractory ceramic fibres	0.83–4.0	0.49–9.2
Use of refractory ceramic fibres	–	2.7–17.1

From United Kingdom Factories Inspectorate (1987)

[a] < 3 μm in diameter

[b] Determined by TEM

In an effort to characterize better the concentrations of airborne fibres associated with the installation of glass fibre insulation in homes, and to determine the proportion of airborne fibres that were glass fibres, a survey of batt and loose fill insulation in the USA was undertaken in the early 1990s (Jacob *et al.*, 1992). The results of this survey are presented in Tables 42 and 43. The arithmetic mean concentration of total airborne fibres present during the installation of batt insulation was 0.22 fibre/cm^3. Approximately 60% of this total was glass fibres and approximately 30% of these glass fibres were respirable (< 3 μm in diameter). During the application of blowing wool, the total concentrations of airborne fibres were higher, with arithmetic means of 1.0 and 2.1 fibres/cm^3, depending upon the product type. The mean concentrations of glass fibres were 0.7 and 1.7 fibre/cm^3 and those of respirable glass fibres were 0.3 and 0.8 fibre/cm^3, respectively in batt and loose fill installation. Approximately 70–80% of the total airborne fibres measured were glass fibres.

A survey of MMVF insulation products was also conducted at several industrial construction sites where workers were installing or removing insulation in Montreal, Quebec, Canada in the early 1990s. The samples were analysed using both PCOM and TEM and the results are presented in Table 44 (Perrault *et al.*, 1992).

In the largest survey of the exposure of end-users to airborne MMVF fibres (Lees *et al.*, 1993; Breysse *et al.*, 2001), nearly 1200 samples were collected during the fabrication and installation of MMVF products for residential, commercial and industrial use. The samples were analysed using PCOM or SEM, and the results of the PCOM are presented in Tables 45 and 46. The results indicated that during installation of MMVF insulation in homes, the geometric mean concentrations of airborne fibres were less than 1.0 fibre/cm^3 for all exposure groups, except for installers and feeders of glass fibre loose-fill insulation without binder (7.7 fibres/cm^3 for installers and 1.7 fibre/cm^3 for feeders), and for installers of loose rock (stone) and slag wool (1.9 fibre/cm^3) (Lees

Table 42. Arithmetic mean concentration of airborne fibres (fibre/cm^3) associated with installation of batt insulation

Sampling location	Total fibres[a]	Total glass fibres[b]	Respirable fibres[c]	Respirable glass fibres[d]
Before installation				
Arithmetic mean	0.008	0.001	0.002	0.00005
95% confidence limits[e]	0.006–0.012	0.001–0.002	0.001–0.003	0.00001–0.00011
95th percentile[f]	0.026	0.003	0.006	0.0003
Number of samples	26	26	15	15
Installers				
Arithmetic mean	0.22	0.13	0.059	0.042
95% confidence limits	0.18–0.27	0.099–0.16	0.049–0.073	0.032–0.052
95th percentile	0.56	0.34	0.14	0.11
Number of samples	60	60	32	32
After installation				
Arithmetic mean	0.012	0.004	0.001	0.0002
95% confidence limits	0.005–0.028	0.001–0.010	0.001–0.002	0.0001–0.0004
95th percentile	0.021	0.006	0.003	0.0009
Number of samples	26	26	15	15

From Jacob *et al.* (1992)

[a] Total fibres, NIOSH 7400 A rules, both filters and cowls

[b] Total glass fibres, NIOSH 7400 A rules, both filters and cowls, glass fibres only

[c] Respirable fibres, NIOSH 7400 B rules, both filters and cowls

[d] Respirable glass fibres, NIOSH 7400 B rules, both filters and cowls, glass fibres only

[e] 95% confidence intervals of the arithmetic mean

[f] 95th percentile of the data (95% of all measurements were less than this value)

et al., 1993). The geometric mean concentrations of airborne fibres during the fabrication and installation of commercial and industrial MMVF insulation products were all found to be less than 1.0 fibre/cm^3 (Breysse *et al.,* 2001).

Koenig and Axten (1995) reviewed the concentrations of airborne fibres associated with the installation of rock (stone) and slag wool ceiling tiles and various other commercial and industrial insulation products manufactured from rock (stone) and slag wool in the USA. The arithmetic mean concentration of airborne fibres measured during the installation of wet-felted and moulded acoustical ceiling tiles was 0.26 fibre/cm^3 with a range of 8-h TWA exposure from 0.02–0.82 fibre/cm^3. The concentrations of airborne fibres measured for certain other rock (stone) and slag wool products are presented in Table 47. The overall mean exposure during installation operations involving these products was 0.09 fibre/cm^3 and all the 8-h TWAs measured were well below 0.5 fibre/cm^3.

Table 43. Arithmetic mean concentration of airborne fibres (fibre/cm^3) associated with installation of cubed and milled blowing-wool insulation

Sampling location	Total[a]	Total glass fibres[b]	Respirable fibres[c]	Respirable glass fibres[d]
Before installation				
Arithmetic mean	0.004	0.0008	0.001	0.0001
95% confidence limits[e]	0.003–0.005	0.007–0.001	0.001–0.002	0.00005–0.0002
95th percentile[f]	0.008	0.002	0.002	0.0004
Number of samples	38	38	24	24
Loader, cubed				
Arithmetic mean	0.38	0.20	0.12	0.084
95% confidence limits	0.33–0.42	0.17–0.23	0.10–0.15	0.06–0.10
95th percentile	0.80	0.50	0.30	0.24
Number of samples	99	99	49	49
Loader, milled				
Arithmetic mean	0.54	0.37	0.22	0.18
95% confidence limits	0.42–0.69	0.26–0.50	0.16–0.31	0.11–0.26
95th percentile	1.25	0.99	0.45	0.42
Number of samples	31	31	16	16
Installer, cubed				
Arithmetic mean	1.03	0.68	0.37	0.30
95% confidence limits	0.93–1.13	0.60–0.76	0.31–0.44	0.24–0.35
95th percentile	1.95	1.66	0.79	0.71
Number of samples	100	100	52	52
Installer, milled				
Arithmetic mean	2.1	1.7	0.91	0.82
95% confidence limits	1.5–2.7	1.2–2.5	0.58–1.3	0.53–1.3
95th percentile	6.0	5.2	2.8	2.7
Number of samples	31	31	15	15
After installation				
Arithmetic mean	0.004	0.001	0.001	0.0001
95% confidence limits	0.003–0.004	0.001–0.002	0.0007–0.002	0.00005–0.0002
95th percentile	0.008	0.003	0.002	0.0003
Number of samples	62	62	38	38

From Jacob *et al.* (1992)

[a] Total fibres, NIOSH 7400 A rules, both filters and cowls

[b] Total glass fibres, NIOSH 7400 A rules, both filters and cowls, glass fibres only

[c] Respirable fibres, NIOSH 7400 B rules, both filters and cowls

[d] Respirable glass fibres, NIOSH 7400 B rules, both filters and cowls, glass fibres only

[e] 95% confidence intervals of the arithmetic mean

[f] 95th percentile of the data (95% of all measurements were less than this value)

Table 44. Concentrations of respirable fibres on construction sites as measured by phase-contrast optical microscopy

Sites	No. of samples	Geometric mean (fibre/cm^3)
Glass wool	17	0.01
Rock (stone) wool (blown)	10	0.32
Rock (stone) wool (sprayed on)	16	0.15
Refractory ceramic fibres		
Site A (patching furnace insulation)	40	0.64
Site B (installing insulation panels)	41	0.39
Site C (installing refractory bricks)	46	3.51

From Perrault *et al.* (1992)

Additional information on exposure during the installation of rock (stone) and slag wool products (see Table 26) is included in the aforementioned NAIMA database (Marchant *et al.*, 2002). These results essentially substantiate those of Koenig and Axten (1995). Further data on the concentrations of airborne fibres associated with the installation of glass wool products as presented in Tables 48 and 49 (Marchant *et al.,* 2002) are consistent with the results obtained by Lees *et al.* (1993).

Data on the concentrations of airborne fibres measured in the USA during the installation and removal of refractory ceramic fibre products have been given in Table 29 (Maxim *et al.*, 1997, 2000a). The overall arithmetic mean of TWA values measured from 1993–96 was 0.41 fibre/cm^3. The average concentrations of airborne refractory ceramic fibres in the workplace were higher for insulation removers. The arithmetic mean actual TWA over the period 1993–96 was 1.2 fibre/cm^3 (Maxim *et al.*, 2000a). [The Working Group noted that the composition of refractory ceramic fibre at removal may be different from its composition at assembly.]

Finally, the survey of plants manufacturing glass wool, rock (stone) wool and refractory ceramic fibre and of user industries in Australia which was discussed previously, produced considerable data on exposure to airborne fibres from MMVF products during their installation and removal (Yeung & Rogers, 1996). These data, summarized in Table 50, indicate that, as was the case for manufacturing operations, the geometric mean exposure of individuals installing and/or removing these insulation products was below the established exposure standard of 0.5 fibre/cm^3 (Yeung & Rogers, 1996).

Table 45. Summary of 8-h TWA estimates of exposure to fibres during insulation of dwellings by product/occupational category as measured by phase-contrast optical microscopy

MMVF product	Occupation	No. of TWAs	Fibre concentration (fibre/cm^3)[a]			
			Mean	Standard deviation	Geometric mean	Geometric standard deviation
Fibre glass batts	Installer	19	0.06	0.05	0.05	2.41
Rock (stone) and slag wool batts	Installer	6	0.11	0.04	0.10	1.45
Fibrous glass loose-fill insulation with binder	Installer	8	0.15	0.13	0.09	3.82
	Feeder	7	0.05	0.04	0.03	3.06
Fibrous glass loose-fill insulation without binder	Installer	4	1.96	1.23	1.52	2.56
	Feeder	1	0.85	–	–	–
Rock (stone) and slag wool, loose	Installer	5	0.97	1.06	0.52	3.76
	Feeder	4	0.18	0.15	0.14	2.20

From Lees *et al.* (1993)

[a] Respirable fibres (≤ 3 µm in diameter) only

Table 46. Summary of task length average exposure estimates by product/occupation as measured by phase-contrast optical microscopy

MMVF product	Occupation	No. of TLAs[b]	Fibre concentration (fibre/cm^3)[a]			
			Mean	Standard deviation	Geometric mean	Geometric standard deviation
Glass fibre duct board	Fabricator	14	0.05	0.10	0.03	2.30
	Installer	4	0.03	0.01	0.03	1.40
Glass fibre duct liner	Fabricator	26	0.04	0.06	0.03	2.31
	Installer	5	0.32	0.06	0.32	1.17
Glass fibre duct wrap	Installer	4	0.68	0.97	0.35	3.33
Glass fibre pipe and vessel insulation	Installer	23	0.04	0.04	0.03	2.54
Rock (stone) and slag wool ceiling tiles	Installer	14	0.24	0.12	0.22	1.64
Glass fibre batts (prefabricated homes)	Installer	3	0.19	0.06	0.19	1.33
Rock (stone) and slag wool, loose fill (prefabricated homes)	Installer	5	0.13	0.06	0.11	1.71
Rock (stone) and slag wool building safing	Installer	5	0.16	0.12	0.12	2.21
General glass fibre products	Fabricator	22	0.16	0.12	0.11	2.84

From Breysse *et al.* (2001)

[a] Respirable fibres (< 3 µm in diameter) only

[b] TLA, task-length average. The geometric mean TLAs for each product/occupational group are generally slightly lower than the arithmetic mean concentrations.

Table 47. Exposure to respirable fibres associated with installation of insulation products manufactured from rock (stone) and slag wool

Product installed	Area type[a]	Tasks performed	Fibre concentrations (fibre/cm^3)		
			No. of samples	8-h TWA	Range
Attic insulation 1	Confined	Blower	5	0.07	0.04–0.62
	Open	Helper	3	0.03	0.05–0.13
	Confined	Blower	4	0.19	0.02–0.30
Attic insulation 2	Open	Helper	4	0.05	0.02–0.09
Sound attenuation blanket	Moder. open	Cutting/place	9	0.16	0.11–0.24
Insulation fabrication shop	Open	Cutting/assembling/packing	5	0.07	0.03–0.11
		Cutting/assembling/packing	4	0.07	0.03–0.19
		Cutting/assembling/packing	4	0.05	0.03–0.07
		Cutting/assembling/packing	4	0.04	0.03–0.07
		Assembling/packing	4	0.06	0.02–0.03
Installation of outdoor pipe-covering	Open	Cutting/installation/cover	1	0.02	0.02
		Cutting/installation/cover	2	0.05	0.04–0.05
		Cutting/installation/cover	1	0.05	0.05
Spray-on fire proofing	Open	Nozzle man	8	0.13	0.03–0.29
		Labourer	2	0.02	0.07–0.14
		Pump operator	2	0.01	0.02
Spray-on fire proofing	Open	Nozzle man	8	0.42	0.03–1.10
		Labourer	6	0.09	0.03–0.29
		Labourer	4	0.04	0.01–0.05
		Pump operator	3	0.03	0.01–0.07

From Koenig & Axten (1995)

[a] Confined, confined area such as an attic; moder. open, moderately open areas such as within a factory with no high bay; open, outdoors or in a very large enclosed area

Table 48. Exposure to glass wool fibres by job description

Job description	Sample size	Exposure (fibre/cm^3)			
		Mean	Standard deviation	Median	Range
Assembly	34	0.04	0.06	0.02	0.01–0.35
Feeder	63	0.36	0.37	0.20	0.01–2.18
Installer	232	0.45	0.85	0.18	0.01–7.49
Other[a]	9	0.16	0.14	0.07	0.03–0.37

From Marchant *et al.* (2002) (personal samples; sampling times greater than 4 h; analysed by NIOSH 7400 method with B counting rules)
[a] Includes cutting or sawing with power tools and maintenance

Table 49. Exposure during installation of glass wool by product type and job description

Product type	Job description	Sample size	Exposure (fibre/cm^3)			
			Mean	Standard deviation	Median	Range
Blowing wool with binder	Feeder	6	0.09	0.06	0.06	0.04–0.19
	Installer	13	0.39	0.32	0.28	0.09–1.13
Blowing wool without binder	Feeder	49	0.44	0.39	0.35	0.01–2.18
	Installer	84	0.99	1.21	0.62	0.04–7.49

From Marchant *et al.* (2002) (personal samples; sampling times greater than 4 h; analysed by NIOSH 7400 method using B counting rules)

(*d*) *Exposure in residential, commercial and public buildings*

The exposure of the occupants of a building to airborne MMVFs may occur during installation, maintenance, or removal operations, as a result of physical damage or degradation of insulation or as fibres are released over time. Several studies, using a variety of sampling and analytical techniques, have evaluated and reported on the nature and magnitude of such exposure.

In the late 1960s, concern was expressed over health problems associated with the possible erosion of glass fibre used to line ventilation and heating ducts. Cholak & Schafer (1971) tested six different ventilation-system ducts and found some glass fibres in settled dust, but no evidence of erosion of the fibres. Thirteen air-transmission systems lined with glass fibre were studied to determine their contributions of glass fibres to the air. The average concentrations of glass fibres in ambient air in the air leaving air-supply

Table 50. Exposure to MMVFs during installation and removal

Type of MMVF	Process	Pre-NOHSC standard Typical fibre count (fibre/cm^3), location/job	Type of sample	Post-NOHSC standard respirable fibre count (fibre/cm^3)			
				No.	Range	Geometric mean	Geometric standard deviation
Glass fibre	Installation of bonded products	0.1–0.3 ceiling space < 0.1–3.5 ceiling space, short-term sample < 0.01–0.1 plant room	Personal	23	< 0.01–0.80	0.12	2.23
			Static	29	< 0.01–0.40	0.03	2.74
			Total	52	< 0.01–0.80	0.06	3.14
	Removal of glass fibre products	–	Personal	21	< 0.01–0.20	0.04	2.20
			Static	12	< 0.01–0.03	0.02	1.67
			Total	33	< 0.01–0.20	0.03	2.18
Rock (stone) wool	Installation of bonded products	0.1–0.4 ceiling space 0.01–0.1 lagging of boilers	Personal	42	< 0.01–1.50	0.03	2.71
			Static	303	< 0.01–1.0	0.02	1.87
			Total	345	< 0.01–1.50	0.02	2.07
	Removal of rock (stone) wool products	–	Personal	1	0.5	–	–
			Static	17	< 0.01–0.05	0.01	1.73
			Total	18	< 0.01–0.50	0.04	2.76
Refractory ceramic fibre	Installation of bonded products[a]		Personal	21	< 0.01–1.5	0.04	2.48
	Application of unbonded materials	0.7 firewall 0.03–0.2 fire damper 0.02–1.8 delagging in furnace 0.07–1.5 lagging in furnace 0.01–1.4 lagging of boilers	Personal	28	< 0.01–1.4	0.04	7.12
			Static	99	< 0.01–0.4	0.02	2.60
			Total	127	< 0.01–1.4	0.02	3.63
	Removal of refractory ceramic fibres	–	Personal	13	< 0.01–0.3	0.05	2.99
			Static	62	< 0.01–0.1	0.02	1.86
			Total	75	< 0.01–0.3	0.02	2.21

From Yeung & Rogers (1996)

[a] Mixed fibres (rock (stone) wool and refractory ceramic fibre)

systems, and in building areas were extremely low (below 0.005 fibre/cm^3). In some cases, there was a decrease in the fibre concentration after fibre-containing outdoor air had passed through the air-transmission system (Balzer *et al.*, 1971).

Five studies were conducted in Europe using PCOM combined with PLM as a primary analytical device, and selected buildings that had acoustical ceiling tiles made of MMVF or sprayed-on MMVF ceilings. Rindel *et al.* (1987) reported that in a study in 24 kindergartens in Denmark, all had concentrations of respirable fibres of MMVF below 0.001 fibre/cm^3, but the sampling time was only 1 h. Skov *et al.* (1987) measured the fibre concentrations in 14 Danish town halls and found airborne MMVFs in only one building. Gaudichet *et al.* (1989) studied 79 buildings containing various MMVF products and found concentrations of respirable MMVFs ranging from none detected to 0.006 fibre/cm^3.

Nielsen (1987) and Schneider *et al.* (1990) reported on measurements made in 105 rooms containing acoustical ceiling tiles. The average concentrations of airborne respirable MMVFs were less than 0.0001 fibre/cm^3 and ranged from none detected to 0.002 fibre/cm^3.

Schneider (1986) reported on measurements made in 16 schools and one office building in Greater Copenhagen where the concentrations of airborne respirable MMVFs ranged from non-detectable to 0.08 fibre/cm^3.

Two studies used PCOM to measure the concentrations of airborne fibres before, during and after the installation of MMVF products in homes. In the study of Van der Wal *et al.* (1987) that made measurements in eight homes, the average concentration of fibres just before the installation of insulation began was 0.012 (range 0.001–0.03) fibre/cm^3. During installation, the average peak fibre concentration was 0.03 (range, 0.01–0.65) fibre/cm^3. When measurements were repeated the next day at the same locations, the average concentration had decreased to 0.004 (range, 0.001–0.01) fibre/cm^3. Jacob *et al.* (1992) reported that the mean concentrations of respirable glass fibres measured in 74 homes before and after the installation of batt or blowing wool insulation were 0.0002 fibre/cm^3 or less, while during the installation the mean concentrations of respirable glass fibre were 0.04 fibre/cm^3 during batt installation and 0.30–0.82 fibre/cm^3 during installation of blowing wool insulation. The authors reported that on the night following the completion of the insulation work, the concentration of airborne fibres had dropped to that measured before the insulation work began.

Jaffrey *et al.* (1990) reported the concentrations of airborne MMVF in 11 dwellings in the United Kingdom during and after the disturbance of loft insulation. Approximately 250 samples were collected and analysed by TEM–EDXA and a few additional samples were analysed by PCOM. The TWA concentrations measured over a 4-h period during the physical disturbance of the insulation in the lofts ranged up to 0.03 fibre/cm^3. The personal measurements of exposure to MMVF during this period were up to 0.2 fibre/cm^3. However, no contamination of the living space was detected although the access doors to the lofts remained open throughout the disturbance and sampling period.

Tiesler and Draeger (1993) and Tiesler *et al.* (1993) reported more than 130 measurements of indoor concentrations of airborne fibres made in various buildings. Most samples were collected in offices, but some schools, private houses and laboratories were also sampled. The buildings selected contained visible and uncoated glass and rock (stone) slag wool products which represented worst-case conditions. The authors concluded that the total indoor concentrations of respirable inorganic fibres generally averaged 0.0046 fibre/cm^3, ranging from none detected to 0.038 fibre/cm^3. The fibres of MMVF products comprised 12.5% of the mean total respirable inorganic mineral fibres detected, averaging 0.0006 fibre/cm^3 and ranging from none detected to 0.0057 fibre/cm^3. Thirty-nine simultaneously collected outdoor samples were reported. The concentration of inorganic nonasbestos respirable fibre outdoors averaged 0.00499 fibre/cm^3. The authors concluded that concentrations of fibres indoors and outdoors were generally of the same order of magnitude.

Fischer (1993) reported the concentrations of airborne respirable fibres measured in seven offices, one school and one dwelling, and in a group of six buildings (a shop, offices, school, kindergartens) in which the users had complained about possible exposure to fibre dust from ceiling boards. To ensure a conservative estimate, the ceiling boards in the buildings selected were in direct contact with indoor air. The concentrations of respirable inorganic fibres averaged 0.0018 fibre/cm^3; the concentration of MMVF products was 0.0003 fibre/cm^3 or 17% of the respirable inorganic fibres. The concentration of respirable MMVFs outdoors was of the same order of magnitude.

Dodgson *et al.* (1987b) measured the concentrations of airborne fibres in 10 homes using PCOM and SEM before, 24 h after and 7 days after the installation or disturbance of MMVF insulation in their lofts. The mean concentrations of MMVF measured 24 h after the installation of insulation in new homes was not different from the concentrations measured before work began; the fibre concentrations determined by SEM ranged from 0.0001–0.0003 fibre/cm^3.

Carter *et al.* (1999) reported the concentrations of airborne MMVFs measured in 51 residential and commercial buildings throughout the USA. All samples were analysed by PCOM and 50 randomly selected samples were analysed by SEM–EDXA. The mean concentration of all respirable fibres counted using PCOM was 0.008 fibre/cm^3. Ninety-seven per cent of the respirable fibres identified by SEM–EDXA were determined to be organic in nature. The concentrations of inorganic fibres determined by SEM–EDXA, which included MMVFs, were found to be less than 0.0001 fibre/cm^3.

1.4.2 *Environmental occurrence*

Man-made vitreous fibres may be released into the environment during their production, installation, erosion, removal and/or disposal. However, few studies have attempted to quantify the concentration of MMVFs present in ambient air, and those that have been conducted have often failed to distinguish between MMVFs and mineral fibres or 'other inorganic fibres' or to attempt to define fibre size or chemical composition. Despite these limitations, several studies (described below) have indicated the concentrations of MMVFs which may be present in the general environment.

Spurny and Stöber (1981) identified inorganic fibres in air samples from an urban non-industrial area and in clean rural air in the former Federal Republic of Germany. The total concentrations of fibres ranged from 0.004–0.015 fibre/cm^3. Friedrichs *et al.* (1983) also published data on the number of fibres present in the ambient air in samples collected in the former Federal Republic of Germany during 1982. The concentrations of glass fibre ranged from 0.00036–0.00249 fibre/cm^3 and were higher on week days than at the weekend.

Lanting and Den Boeft (1983) reported a uniform background concentration of non-asbestiform inorganic fibres of 10^4 fibres/m^3 (i.e. 0.01 fibre/cm^3) at all their rural and urban sampling sites in the Netherlands.

Iburg *et al.* (1987) updated earlier studies of concentrations of fibres in the ambient air measured in the former Federal Republic of Germany. The concentrations were reported to range from 0.0008–0.0020 fibre/cm^3 at urban crossroads. Noack and Böckler-Klusemann (1993) published similar findings. They reported concentrations of inorganic fibres > 5 μm length excluding asbestos and gypsum at urban locations in Germany to be 0.00070–0.00325 fibre/cm^3 and Goldmann and Kruger (1989) reported concentrations of 0.00496–0.00589 fibre/cm^3 in urban non-occupational situations. Rödelsperger *et al.* (1989) also published data indicating that the average concentrations of airborne inorganic fibres ≥ 5 μm in length excluding asbestos and gypsum in ambient air exceeded 0.001 fibre/cm^3 in urban and rural areas of Germany, while Schnittger (1993) reported that concentrations of airborne inorganic nonasbestos fibres with diameters below 3 μm in ambient air were of the order of 0.0022 fibre/cm^3 in an urban area of Germany.

Three studies have reported on the concentrations of glass fibres measured in outdoor air in France (Gaudichet *et al.*, 1989), Germany (Höhr, 1985) and the USA (Balzer, 1976). In these studies, the concentrations of glass fibres ranged from 2×10^{-6} fibres/cm^3 in a rural area to 0.0017 fibre/cm^3 near a city. These concentrations were considered to represent a very small percentage of the total fibre and total suspended particulate matter in ambient air.

Most recently, a study of the exposure of individuals to respirable inorganic and organic fibres during everyday activities was conducted (Schneider *et al.*, 1996). Four groups (suburban schoolchildren, rural retired persons, office workers and taxi drivers) containing five persons each were monitored to assess their exposure to fibres for 24 h four times over a 1-year period. The fibres were sized by SEM and the elemental composition of individual fibres was determined by EDXA. For inorganic fibres, excluding asbestos and gypsum, the geometric mean concentration was around 0.005 fibre/cm^3. The proportion of these inorganic fibres that had an elemental composition similar to that of MMVF was less than about one quarter.

1.5 Regulations and guidelines

Many industrialized and developing countries have, or refer to, exposure limit values for inert dusts, 'nuisance' dusts or particles. Several of these countries use the same limit values for insulation wool fibres and dusts (ILO, 2000). Table 51 summarizes the regulations enforced in selected countries. The absence of information for a particular country should not be taken to imply that the country does not have regulations with regard to MMVFs.

In December 1997, the European Union (EU) published the classification of man-made (vitreous) silicate fibres under the Substances Directive (European Commission, 1997). [The Working Group noted that this classification is to be reviewed by the EU by December 2002.] According to the EU system, all MMVF wools are considered to be irritants and are classified for carcinogenicity according to the following rules. Man-made vitreous fibre wools with length-weighted geometric mean diameter, less two standard errors, greater than 6 μm are exempt from carcinogenicity classification. [The Working Group noted that the classification and labelling group of the European Commission has agreed to change 'standard error' to standard deviation.] Untested insulation wool fibres with a diameter ≤ 6 μm and with a content of $Na_2O + K_2O + CaO + MgO + BaO$ that exceeds 18% by weight are classified as category 3, 'possible carcinogen'. If the content of $Na_2O + K_2O + CaO + MgO + BaO$ is less than or equal to 18%, the fibre is classified as category 2, 'probable carcinogen'. A category 3 fibre can be exempted from classification as a possible carcinogen if it fulfils one of the following criteria:

(1) a short-term biopersistence test by inhalation has shown that the fibres longer than 20 μm have a weighted half-life of less than 10 days;
(2) a short-term biopersistence test by intratracheal instillation has shown that the fibres longer than 20 μm have a weighted half-life of less than 40 days;
(3) an appropriate intraperitoneal test has shown no evidence of excess carcinogenicity; or
(4) relevant pathogenicity or neoplastic changes have been found to be absent in a suitable long-term inhalation test.

The protocol by which these criteria are established has been proposed by the European Commission (Bernstein & Riego-Sintes, 1999).

Germany (Bundesgesetzblatt, 2000) has banned the production and use of the following fibre-containing products in building and technical applications for insulation against heat and noise:

- MMVF wools with mass percentage greater than 18% of the oxides of Na, K, Ca, Mg and Ba;
- preparations and articles containing in excess of 0.1% (mass fraction) of MMVF wools.

Table 51. Examples of national regulations and guidelines pertaining to limits for occupational exposure to MMVFs

Country	Reference	Products regulated[a]	Exposure limits	
			Fibre/cm^3	Dust (if no specific limit given for fibres)
Australia	NOHSC (2001)	Synthetic mineral fibres	0.5 respirable	2 mg/m^3 inspirable dust; secondary standard in situations in which almost all the airborne material is fibrous
Austria	ILO (2000)	Man-made vitreous (silicate) fibres	0.5 WHO fibre	
Canada	National Research Council (NRC) (2000)	MMVF insulation wool products	Each province has it own, e.g. Alberta 1 (0.5 for refractory ceramic fibres)	
Denmark	Arbejdstilsynet (2001)	Glass, (rock) stone and slag wool	1 WHO fibre	
Finland	ILO (2000)	None		10 mg/m^3
France	INRS (1999)	Mineral wool fibres	1 for glass, rock (stone) and slag wool, 0.6 for refractory ceramic fibres	
Germany	(see text)			
Italy	ILO (2000)	None	1 (fibre with diameter < 3 μm)	5 mg/m^3 total dust
Japan	ILO (2000)	None		2.9 mg/m^3 respirable dust
Republic of Korea	Kim *et al*. (1999)			Permissible level of exposure for glass and rock (stone) wool is 10 mg/m^3.
Netherlands	ILO (2000)	None	1	

Table 51 (contd)

Country	Reference	Products regulated[a]	Exposure limits	
			Fibre/cm^3	Dust (if no specific limit given for fibres)
New Zealand	NRC(2000)	Man-made mineral fibres	1 (fibre with diameter < 3 µm)	
Norway	ILO (2000)	Synthetic mineral fibres	1	
Poland	NRC (2000)	Man-made mineral fibres	2 (length > 5 µm)	
Sweden	AFS (1996)	Inorganic synthetic fibres	1	
Switzerland	ILO (2000)	Mineral wool	0.5 WHO fibres	
United Kingdom	ILO (2000)	MMVF	2	5 mg/m^3 (fibre or mass limit applies, whichever is achieved first)
USA	(see text)			

Swedish National Board of Occupational Safety and Health (AFS) (1996); Arbejdstilsynet (2001); ILO (2000); INRS (1999); Kim *et al*. (1999); Australian National Occupational Health & Safety Commission (NOHSC) (2001); National Research Council (NRC) (2000)

[a] If None, dust is regulated as inorganic dust.

This regulation does not apply to MMVFs that fulfil one of the following exoneration criteria:

(1) a suitable intraperitoneal test showed no evidence of increased carcinogenicity;

(2) the half-life after intratracheal instillation of 2 mg of a fibre suspension containing fibres of length > 5 μm, diameter < 3 μm, and with a length-to-diameter ratio in excess of 3:1 (WHO fibres) does not exceed a maximum of 40 days;

(3) the carcinogenicity index (KI) (mass percentages of oxides of Na, K, Ca, Mg, Ba and B minus twice the mass percentage of aluminum oxide) is at least 40;

(4) glass fibres developed for high-temperature applications with a classification temperature greater than 1000 °C when their half-life, determined by method 2, above, does not exceed 65 days.

The German TRK Wert (Technical limit value) for fibres has been specified by the Deutsche Forschungsgemeinschaft (2001) as follows:

- High-temperature glass fibres: 0.5 fibre/cm^3
- All other applications: 0.25 fibre/cm^3, except in specific areas where refractory ceramic fibres, polycrystalline fibres or special glass fibres are used: existing installations where refractory ceramic fibres and special-purpose glass fibres are processed, processing of refractory ceramic fibres and polycrystalline fibres; for finishing operations, installation, assembly, mixing, forming, packaging at place of fibre production and polycrystalline fibres for which the limit value of 0.5 fibre/cm^3 is applicable until December 31, 2002.

In the USA, the Occupational Safety and Health Administration (OSHA) has not developed a specific exposure limit for fibres and the limits for total dust (15 mg/m^3) and respirable dust (5 mg/m^3) apply. However, certain organizations and the MMVF industry have issued their own recommendations.

- The American Conference of Governmental Industrial Hygienists (2001) has adopted the following Threshold Limit Values for continuous filament glass fibres, 1 fibre/cm^3 and 5 mg/m^3 respirable dust; for glass wool, slag wool, rock (stone) wool and special-purpose glass fibres, 1 fibre/cm^3; and for refractory ceramic fibres, 0.2 fibre/cm^3.
- In 1999, the US Navy reduced their exposure standard for all MMVFs from 2 fibres/cm^3 to 1 fibre/cm^3 (National Research Council, 2000).
- The Health and Safety Partnership Program (between OSHA, NAIMA and the users) established a limit of 1 fibre/cm^3 for respirable MMVF insulation wools (ILO, 2000; Marchant *et al.*, 2002).
- The Refractory Ceramic Fibers Coalition (RCFC), a trade organization of manufacturers of refractory ceramic fibres in the USA, adopted a recommended exposure guideline of 0.5 fibre/cm^3 in 1997 (Maxim *et al.*, 1997; National Research Council, 2000).

- The International Labour Office has issued a Code of Practice on safety in the use of synthetic vitreous fibre insulation wools (ILO, 2000). The Code of Practice covers general and specific measures for prevention and protection, information, education and training and surveillance of exposure and workers' health.