2. Production, Use, Occurrence and Analysis

2.1 Production and use

(a) *Production*

(i) *Amounts produced*

Rock-/slagwool was first produced in Wales in 1840 (Mohr & Rowe, 1978; Fowler, 1980). By 1885, commercial operations had begun in England (Pundsack, 1976), and soon thereafter they began in Germany (Fowler, 1980; World Health Organization, 1983). The first successful commercial rock-/slagwool plant in the USA began operation in 1897 (Fowler, 1980).

Although a few such plants were in operation in the USA and Europe in the early 1900s, it was not until after the First World War that the industry began to develop and grow (Pundsack, 1976; World Health Organization, 1983). By 1928, there were at least eight plants in the USA, and, by 1939, that number had grown to 25 (Pundsack, 1976), a growth attributable primarily to improvements in glass fibre manufacturing technology (Fowler, 1980; Loewenstein, 1983). Glasswool manufacturers were able to open new markets such as textile manufacturing, while rockwool and slagwool manufacturers continued to compete in the thermal insulation market (Mohr & Rowe, 1978; Fowler, 1980). The number of rockwool and slagwool plants in the USA peaked at between 80 and 90 in the 1950s, and then declined as glasswool began to be used in thermal insulation (Pundsack, 1976). By 1985, there were 58 plants in the USA producing glasswool, rockwool, slagwool or ceramic fibres (US Environmental Protection Agency, 1986). According to the European Insulation Manufacturers' Association, there were 37 rock-/slagwool plants (mainly producing rockwool) and 37 glasswool plants in western Europe and Turkey in 1986.

Production of glass filament began in the USA in the 1930s. By 1985, seven companies were manufacturing textile fibres at 14 plants in the USA (US Environmental Protection Agency, 1986).

Estimated world mineral fibre production for 1973 is presented in Table 9 (World Health Organization, 1983). The quantities of glasswool, rockwool and slagwool products manufactured in the USA in 1977 and 1982 are shown in Table 10 (US Department of Commerce, 1985). The production of glass fibre in the USA from 1975 to 1984 is presented in Table 11 (Anon., 1986). In western Europe, production of glasswool, rockwool and slagwool in 1984 amounted to approximately 1550 million kg. Worldwide production of continuous filament in 1984 was estimated at 1384 million kg (Griffiths, 1986).

Although production of ceramic fibres began in the 1940s, their commercial exploitation did not occur until the early 1970s. World-wide production of ceramic fibres in the early-to-mid-1980s was estimated at 70-90 million kg, with US production comprising approximately half of that amount. With the introduction of new ceramic fibres for new uses, production has increased significantly over the past decade (US Environmental Protection Agency, 1986).

Table 9. Estimated world production of man-made mineral fibre materials in 1973 (million kg)[a]

Location	Insulation		Textile		Total	
	Quantity	%	Quantity	%	Quantity	%
Europe	1800	48	345	40	2145	47
Western	1200	32	260	30	1460	32
Eastern	600	16	85	10	685	15
North America	1600	43	400	46	2000	43
Japan	200	5	100	12	300	7
Australia	30	1	–	–	–	–
Central/South America	120	3	20	2	140	3
World	3750		865		4585	

[a]From World Health Organization (1983)

Table 10. Quantities of glasswool, rockwool and slagwool products produced in the USA (million kg)[a]

Product	1977	1982
Mineral wool for thermal and acoustical envelope insulation (for insulating homes and commercial and industrial buildings) made from fibre produced in the same establishment[b]		
Loose and granulated fibre	373.2	327.2
Building batts, blankets and rolls (in thermal resistance values)		
R-19.0 or more	359.9	530.0
R-11.0 to R-18.9	403.9	418.4
R-10.9 or less	NA	52.3
Acoustical, such as wall and ceiling	NA	46.3
Mineral wool for industrial, equipment and appliance insulation made from fibre produced in the same establishment		
Flexible blankets, including fabricated pieces, rolls and batts		
Plain	153.9	173.2
Coated	16.0	21.4
Faced and metal meshed	24.0	
Special purpose insulation pieces such as automobile, appliance and aerospace items and original equipment parts	11.3	11.5
Other blocks and boards	22.0	10.0
Pipe insulation	22.0	26.8
Acoustical, including pads, boards and patches	24.0	NA

Table 10 (contd)

Product	1977	1982
Mineral wool for industrial, equipment and appliance insulation made from fibre purchased or transferred from other establishments		
Flexible blankets, including fabricated pieces, rolls and batts		
Plain	13.9	NA
Coated	0.5	NA
Special purpose insulation pieces such as automobile, appliance and aerospace items and original equipment parts	8.3	NA
Other blocks and boards	24.0	NA
Pipe insulation	8.5	NA

[a]From US Department of Commerce (1985)

[b]Based on US dollar value; larger quantities are made into thermal and acoustical insulation at establishments other than those producing the fibre, but production data are not available.

NA, not available

Table 11. Glass fibre production in the USA (million kg)[a]

Year	Quantity
1975	247.88
1976	306.90
1977	357.30
1978	419.04
1979	460.36
1980	393.62
1981	472.61
1982	408.15
1983	530.27
1984	632.88

[a]From Anon. (1986)

(ii) *Methods of production*

Mineral fibre products are generally made in a three-step process: (1) fusion of raw materials, (2) fibre formation and (3) the conversion of fibres into the commercial product. Step 1 is the fusion (melting and mixing) of raw materials in a furnace. Raw materials are selected to impart the desired properties to the product. The liquid is drawn from the furnace to produce a preform for remelt at some future date or flows directly to a fibre-production device. Step 2 consists of fibre formation. Fibres are made by directing a jet of hot gas at the liquid stream or by centrifugal attenuation. Fibres drawn (extruded) through nozzles are called filaments. In step 3, fibres are converted into commercial products by chemical treatment and formation of blankets, mats, yarns, cloth, moulded shapes and other product types.

Glasswool

Glass fibre may be produced in two steps (marble melt process) or in a single step (direct melt process). In the marble melt process, a glass-making furnace is linked to a forehearth and to machines for converting the melt into marbles. The furnace fuses the raw material and homogenizes the melt. Homogenization occurs in two zones of the furnace, called the refining zone and the working zone. Within the refining zone, the raw material is liquefied; as the melt passes to the working zone, the temperature decreases and brings the melt to its 'working' or processing viscosity — 500–1000 poises. The melt exits through the supply channel or forehearth to the marble-making machine. The preformed marbles can be stored, distributed and subsequently remelted for formation into fibres. In the direct melt process, the glass-making furnace is linked to the forehearth and to a bushing, from which the glass is directly formed into fibres. Glass-making furnaces are heated by gas, oil or electricity (Mohr & Rowe, 1978; Loewenstein, 1983).

The principal ways in which glasswool is formed are spinning, flame attenuation and the rotary process (Pundsack, 1976; Mohr & Rowe, 1978).

The spinning process was developed in 1955 as an improvement over the steam-blown process. The raw material is cupola-melted, and molten material falls onto a series of rapidly rotating wheels. The wheels induce attenuation as the fibres fall from wheel to wheel. The fibres produced are finer and longer than those that are steam-blown, making them more suitable for use as insulation (Pundsack, 1976; Mohr & Rowe, 1978).

Flame attenuation, developed in the middle-to-late 1940s, is adaptable to either the direct melt or the preform melt process. In this method, primary glass fibres are drawn to approximately 1 mm in diameter, aligned in a uniform array and introduced into a jet flame blast. Fibres with diameters as small as 0.05 μm can be produced by this method (Mohr & Rowe, 1978).

The rotary process is the result of a series of improvements made to bulk fibre production. The resultant fibre is qualitatively equivalent to those produced by the flame attentuation method, but considerably greater output can be achieved. In this process, the molten media fall into a rapidly rotating hollow cylindrical unit with holes in its vertical side walls. Centrifugal force extrudes the glass steam through the holes of the cylinder, where the molten fibres are further attenuated by peripherally located jet flame burners (Pundsack, 1976; Mohr & Rowe, 1978).

Glass filaments

The production of glass filament differs from that of glasswool, rockwool or slagwool. Nozzles are attached to the bushing on the forehearth, and mechanical drawing is used to form the primary package of fibre strand — the cake. A fine mist of water is sprayed onto the strands as the filaments leave the bushing, and a lubricating sizing is applied before the strands are gathered and wound into a cake. Filament attenuation begins when the hot melt is exuded through the nozzle and ends when it enters the water mist. The total distance travelled during the process of drawing and freezing is usually 10–20 mm (Lee, 1983). Limits to the rate of attenuation appear to be based on the specific type of fibre being produced and

the size of the nozzle used in the process. The rate of attenuation is usually 3000–4000 m/min (Loewenstein, 1983).

In the manufacture of continuous glass fibre products, the fibres are first combined in the form of chopped strand mats, continuous strand mats, yarns and yarn fabrics, roofing or surface tissue, rovings and roving cloth. The combining of fibre strands to produce these intermediate products requires various types of secondary processing and treatment (Loewenstein, 1983).

Chopped strand mat is a chemically bound fabric consisting of strands 25–50 mm in length. The starting material for chopped strand mats is usually a cake — the primary package of fibre strands. Fibre strands from the cakes are fed into the forming section, where they are chopped and distributed uniformly over the width of the belt. After cutting, the chopped fibres are dropped onto a conveyor for magnetic sifting to remove any pieces of broken blade introduced by the chopping process. A binder is applied, and the chopped strands are passed through an oven, which removes any residual water and cures the binder. Binders that are commonly used are powdered fusible polyesters and polyvinyl acetate emulsions. Once outside of the oven, the product is immediately passed between water-cooled rollers to consolidate the outer layers of the mat (Loewenstein, 1983).

The basic yarn product is formed by twisting a single strand drawn from a cake. Cabled yarns are formed by simultaneously twisting several strands together; the twisting of 40 strands or more constitutes a cord. Twisting is carried out by feeding strands to a bobbin at a controlled rate (Loewenstein, 1983).

Roofing mat or surface tissue is manufactured from chopped fibres. The fibres are suspended in water and passed to a screen, where they are deposited. A conveyor belt carries the fibres to the binder application area and then to an oven for resin curing. The primary binder used in this process is a urea-formaldehyde resin in solution with bitumen (Loewenstein, 1983).

Rovings are manufactured by winding many strands in parallel. Roving cloth is manufactured by the traditional method of cloth making, which involves beaming the yarn for the warp, spooling some of the yarn for the weft, weaving and finishing. The market for such cloth has declined, although it is the highest quality glass-reinforcing material. Once woven, roving cloth requires no additional treatment to give high-quality laminates. It is sometimes used as an alternative to chopped strand mat (Loewenstein, 1983).

Rockwool and slagwool

In the production of rockwool and slagwool, the raw materials are loaded into a cupola, an upright cylindrical furnace, in alternating layers with batches of coke. The coke is burnt, generating temperatures of approximately 1650°C, to melt the raw materials. The molten stream issues from a hole in the bottom of the cupola and is made into fibres (Pundsack, 1976; Fowler, 1980).

Fibres are formed by directing a jet of hot gas onto the falling molten stream, which breaks it into small globules that then tail out, producing fibres with semispherical heads. The heads detach as the materials cool, producing fibres and shot (cooled heads) (Pundsack, 1976; Fowler, 1980). In the early 1940s, the Powell or dry process was developed in which a

group of rotors operating at high centrifugal speeds mechanically attenuate the molten stream (Fowler, 1980). The Downey process, developed at about the same time as the Powell process, combines a spinning rotor with steam attenuation. The molten stream is distributed in a thin pool over the surface of a dish-shaped rotor and flows over its edge, where it is caught up in a high-velocity stream flow surrounding the dish and is fiberized (Pundsack, 1976; Fowler, 1980). The products of the Powell and Downey processes have a relatively high shot content (Pundsack, 1976). Regardless of the manufacturing process, a substantial fraction of the molten raw material becomes shot rather than fibres. Commercial standards for mineral wool insulation specify an upper limit on the shot content of the product, because it is an ineffective insulator (Fowler, 1980).

Raw fibre is sprayed immediately after its formation with a binder and a lubricating oil to reduce breakage and prevent dustiness (Fowler, 1980; World Health Organization, 1983). Binder materials, such as urea-formaldehyde and phenol-formaldehyde resins, are used; other binder solutions are melamine resins, silicone compounds, soluble and emulsified oils, surfactants, extenders and stabilizers. Silicon compounds are used to impart water repellancy to the fibre, and soluble and emulsified oils provide lubrication. Another function of binders is to provide an interface between the vitreous material and added dyes or resins (Loewenstein, 1983; World Health Organization, 1983). The binder content of the finished products depends on the end-use application of the fibres; normally, less than 5% is added to insulation products.

After application of binder, the fibre is conveyed either to temporary bulk storage or directly to a compression bailing machine or bagging station. Further processing may then occur, depending on the intended use of the materials. When the end-use is pouring wool, the loose fibre is passed between counter-rotating toothed drums, forming approximately 2.5-cm wool pellets that can be more easily handled. Should the product require moderate or substantial structural rigidity or stability, a resin may be added immediately after or in place of the oil treatment. Other rockwool products require more complex finishing; for example, residential structural insulation is often covered with a vapour barrier on one side and untreated paper on the other. For industrial insulation, a wire mesh covering is often used (Fowler, 1980).

In 1980, approximately 70% of the rockwool or slagwool sold in the USA was produced from blast furnace slag. Most of the remainder was produced from copper, lead and iron smelter slag. A small amount was produced with natural rock, which is usually added to the slag to impart flexibility to the fibres (Fowler, 1980). In Europe, slags have been used to a lesser extent (Cherrie & Dodgson, 1986).

Ceramic fibres

Ceramic fibres are produced primarily by blowing and spinning; colloidal evaporation, continuous filamentation and whisker-making technologies (vapour-phase deposition) are used to a lesser extent, mainly for special applications (Arledter & Knowles, 1964).

In the steam-blowing system, natural minerals (kaolin clay) or synthetic blends of alumina and silica are fused in an electric furnace, and the melt is drawn off and blown by

pressurized steam or other hot gas. The fibres are collected on a screen and may be processed to remove pelletized material or shot (Arledter & Knowles, 1964; Miller, 1982).

As with the spinning processes for glass and rock fibres, those for ceramic fibres produce a high proportion of long, silky fibres and a relatively low proportion of shot, in contrast to the blowing methods. In this method, a stream of molten material is forced onto rapidly rotating discs, which throw off the molten material tangentially, transforming it into a fibrous form (Arledter & Knowles, 1964; Miller, 1982).

Ceramic fibres of alumina, zirconia, silica, mixtures of zirconia and silica, and thoria have been prepared through evaporation of a colloidal suspension (McCreight *et al.*, 1965). An example of this method is the sol process, which is used to produced the silica-stabilized alumina fibre, Saffil® (Miller, 1982).

The rayon spinnerette method has been used to produce gamma-alumina-spinel, alumina, zircon, alumina-silica mixed oxide, zirconia and titania fibres. Named for its similarity to the technique used to produce rayon thread, this wet spinning process involves dissolution of the raw materials in a suitable solvent and subsequent extrusion of the solution into a liquid bath, where a filament is formed by a combination of precipitation, coagulation and regeneration. Subsequent firing at 1550°C yields polycrystalline fibres (McCreight *et al.*, 1965; Rebenfeld, 1983).

Other special ceramic fibres, in particular those composed of nonoxide materials, have been produced by a vapour-phase deposition technique in which a volatile compound of the desired coating material is reduced or decomposed on a resistively heated substrate, such as tungsten wire. The feasibility of making composite polycrystalline filaments by this method has been demonstrated with such materials as boron, boron carbide, silicon carbide and titanium boride (McCreight *et al.*, 1965); boron and silicon carbide fibres have been produced commercially. Annual US production in 1986 was 15.9–22.7 tonnes boron fibre and 0.9 tonnes silicon carbide filaments. Materials filamentized by this technique display good mechanical properties but in their present state of development are the least economical (Anon., 1987b).

Vapour-phase deposition processes are also used to manufacture another class of fibres, known as 'whiskers'. Whiskers are monocrystalline ceramic materials with high strength and micron-sized widths or diameters. Whiskers first came under intense study in 1952 after Herring and Galt determined experimentally that the strength of tin whiskers was an order of magnitude greater than that of ordinary tin. The increased strength of whiskers is attributed to their crystalline perfection and their small dimensions, which minimize the occurrence of the defects that are responsible for the low strength of materials in bulk form. High strength, high elastic modulus, low density and a high melting-point make whiskers useful as reinforcing agents for metals, plastics and ceramics (Levitt, 1970; Parratt, 1972).

Whiskers are produced mainly by vapour-phase techniques, characterized by three methods in which the driving force is primary recrystallization or a step-wise decrease in supersaturation. The methods are evaporation-condensation, chemical reduction and vapour-phase reaction (Campbell, 1970). Although the production of whiskers has developed rapidly in recent years, volumes are still small compared with those of other, more conventional products.

(*b*) *Use*

(i) *Glass fibre, rockwool and slagwool*

The overwhelming majority of glasswool, rockwool and slagwool is produced for thermal and acoustical insulation applications in construction and shipbuilding (Mohr & Rowe, 1978; US Department of Commerce, 1985). In 1980, approximately 80% of the glasswool produced for structural insulation was used in houses (US Environmental Protection Agency, 1986). Rockwool and glasswool, in the form of loose-bagged wool, is pneumatically blown or hand-poured into structural spaces, such as between joints and in attics (Mohr & Rowe, 1978; Fowler, 1980). Bulk rockwool and glass-fibre rovings are incorporated into ceiling tile for fire resistance and thermal and sound insulation (Fowler, 1980; Lee, 1983). Batts, blankets and semirigid boards made of glass- or rockwool fibres are commonly used between structural members of residential and commercial buildings (Mohr & Rowe, 1978).

Plumbing and air-handling systems also require insulation. Pipes are insulated against heat flow with prefabricated sleeves made from moulded glass or rockwool fibres impregnated with phenolic resins and may be used either indoors or outdoors. Sleeves may be applied to steam lines, drains or water lines. Sheet-metal ducts and plenums of air-handling systems are often insulated with flexible blankets and semirigid boards usually made of glass fibre. These forms of insulation may be applied internally or externally throughout the air-handling system (Mohr & Rowe, 1978; Fowler, 1980).

Small-diameter glass fibres (0.05–3.8 μm) have been used in air and liquid filtration, and glass-fibre air filters have been used in furnaces and air-conditioning systems. Glass-fibre filters have been used in the manufacture of beverages, pharmaceuticals, paper and other products, such as swimming-pool filters, and for many other applications (Mohr & Rowe, 1978).

Glass fibre used for aerospace engineering is applied in the form of batts, blankets and moulded parts to the inside of the exterior fuselage skin between the ribs. Special high temperature-resistant materials are applied to high-velocity aircraft at the nose, wing and empennage tips. Marine products have glass or rockwool fibres built into structural components for thermal, acoustical and fire protection. Specific areas of use include motor shrouds, cabin walls and around turbines and similar gear (Mohr & Rowe, 1978).

In addition, glass fibres have a number of uses specific to a particular end-product. Most glass fibre is sold as chopped strand mats, continuous strand mats, rovings, woven rovings, chopped fibres, yarns and yarn fabrics, and roofing mat or surfacing tissue (Loewenstein, 1983). These products have over 30 000 documented uses (Dement, 1973), the most common of which are detailed here. Chopped strand mats are used to reinforce thermoplastics in the construction of boat hulls and decks, vehicle bodies, sheeting and chimneys. This type of mat is used when the laminate is made from the open mould process. Continuous strand mats are used in laminate production when press moulding is employed and to improve the appearance and strength of the laminates. Overlay mats are sometimes used as an alternative to continuous strand mats. Rovings have a variety of uses. They may be chopped to produce chopped strands, woven to produce roving cloth, or wound onto a male mould to

give rise to convex-shaped composites such as aircraft nosecones (radomes). Rovings can undergo pultrussion, a process for making reinforced plastic parts in continuous lengths and of uniform cross-section, to produce structural shapes such as beams, rails, rods and tubes for use in frames and ladders and for purposes where electrical insulation is required. If rovings are chopped and impregnated with polyester resin and left uncured, the material may be rolled out into sheet moulding or left as bulk material for future moulding applications. Chopped fibres are primarily used in the production of roofing mat, reinforcement of thermoplastics (as chopped strand mats) and as filler for polyurethane in reaction injection moulding. They can also be incorporated into a polyester resin to form a gelatinous pre-mix for future use. Glass-fibre yarns are used in the manufacture of glass cloth and heavy-duty cord for tyre reinforcement. The major uses of glass cloth are for high-quality printed circuit boards, aeroplane structures, and for fireproof textiles, such as draperies and emergency protective clothing. Roofing mat is commonly used to cover concrete or wooden roofs and may be substituted for linoleum floor covering when impregnated with polyvinyl chloride (Loewenstein, 1983).

Continuous filament fibre glass is used as a conductor of light (fibre optics) for communications, light and image transmission and decoration (Mohr & Rowe, 1978).

(ii) *Ceramic fibres*

Ceramic refractory fibres are also used as insulation materials. Due to their ability to withstand high temperatures, they are used primarily for lining furnaces and kilns. End-products may be in the form of blankets, boards, felts, bulk fibres, vacuum-formed or cast shapes, paper and textile products (Table 12). Their light weight, thermal shock resistance and strength make them useful in a number of industries (Mohr & Rowe, 1978; US Environmental Protection Agency, 1986).

Table 12. Estimated US consumption of alumina-silica ceramic fibres in 1983[a]

Product	Consumption (million kg)	Approximate % of total
Blanket and felt	20.5	50%
Bulk fibre	4.1	10%
Vacuum-formed shapes	5.0	12%
Boards and blocks	3.2	8%
Paper	2.3	6%
Other[b]	5.9	14%

[a]From US Environmental Protection Agency (1986)

[b]Includes coatings, sprays, castables, textiles and miscellaneous

High temperature-resistant ceramic blankets and boards are used in shipbuilding as insulation to prevent the spread of fires and for general heat containment. Blankets, rigid board and semirigid board can be applied to the compartment walls and ceilings of ships for

this purpose. Ceramic blankets are used as insulation for catalytic converters in the automobile industry and in aircraft and space vehicle engines. In the metal industry, ceramic blankets are used as insulation on the interior of furnaces. Boards are used in combination with blankets for insulation of furnaces designed to produce temperatures up to approximately 1400°C. Ceramic boards are also used as furnace and kiln back-up insulation, as thermal covering for stationary steam generators, as linings for ladles designed to carry molten metal and as cover insulation for magnesium cells and high-temperature reactors in the chemical process industry (Mohr & Rowe, 1978; Miller, 1982).

Ceramic felts are used in the metal industry for furnace insulation, firewall protection, packing for stress-relieving of welds, insulation for heat-treating ovens and kilns, and coverings for hot ingots during transport. Felts are used as catalytic combustion surfaces in the hot-forming process for production of metals such as beryllium and titanium. They have also been used as gas turbine silencers and mufflers, high-temperature gaskets and seals for expansion joints, and for high-temperature filtration. Some typical applications for bulk ceramic fibres are as filler for expansion joints, as stuffing wool and as construction material for furnaces and ovens. In steel mills, aluminium and brass foundries, and glass manufacturing operations, bulk fibres are used as loose-fill insulation and as a raw material for casting shapes (Mohr & Rowe, 1978; Miller, 1982).

Approximately 20% of the ceramic fibre produced is cast shaped (Miller, 1982). Bulk fibres are mixed in an aqueous suspension with clays, colloidal metal oxide particles and organic binders. The mix is poured into moulds with fine-mesh screen surfaces to produce such shapes as flat discs with flanges, short pipes, tubing, elbow bends, cores and closed-end cylinders. These cast-shaped ceramic end-products are widely used in smelting, casting and foundry operations as riser sleeves, feeder tubes and reusable surface insulation tiles. Such tiles are used to cover 70% of the body of space shuttles and can withstand temperatures as high as 1260°C (Mohr & Rowe, 1978; Miller, 1982).

Ceramic-fibre paper is used in end-products such as gaskets, combustion chamber linings, metal trough backups, hot tops and ingot moulds, and can be used as a parting agent in metal- and ceramic-forming processes. The ceramic paper may be rolled to form laminated tubes and discs or die cut for electronic components (Mohr & Rowe, 1978; Miller, 1982).

Ceramic textile products, such as yarns and fabrics, are used extensively in such end-products as heat-resistant clothing, flame curtains for furnace openings, thermocoupling and electrical insulation, gasket and wrapping insulation, coverings for induction-heating furnace coils, cable and wire insulation for braided sleeving, infrared radiation diffusers, insulation for fuel lines and high-pressure portable flange covers. Fibres that are coated with Teflon® are used as sewing threads for manufacturing high-temperature insulation shapes for aircraft and space vehicles. The spaces between the rigid tiles on space shuttles are packed with this fibre in tape form (Miller, 1982).

Nonoxide fibres, such as silicon carbide, boron nitride and silicon nitride, can be dispersed in resins and cast to form special electrical and aircraft parts such as radomes (microwave windows). These fibres are also used as reinforcing inclusions in metals such as aluminium, gold and silver (Miller, 1982).

Applications of ceramic fibres in the automobile industry are being investigated in Japan, western Europe and the USA (van Rhijn, 1984; Walzer, 1984; Anon., 1987c). Ceramic materials may be a substitute for those automobile materials that are insufficiently resistant to heat and corrosion, or in applications where expensive alloys are needed. These areas include prechambers and swirl chambers in indirect-injection diesel engines and the piston crown in direct-injection diesel engines. Examples of engine components that have been made of ceramic metals are combustion chambers, turbine nozzle rings, turbocharger turbine rotors and heat exchangers (Walzer, 1984).

(*c*) *Regulatory status and guidelines*

Statements concerning regulations and guidelines are included as indications of potential exposures. The absence of information on regulatory status for a country should not be taken to imply that that country does not have regulations with regard to man-made mineral fibres. In several countries in which specific exposure standards have not been established for man-made mineral fibres, exposure limits for total or respirable inorganic dust are applied.

Czechoslovakia

The average maximum allowable concentration for glass fibre is 8 mg/m^3 (International Labour Office, 1980).

Federal Republic of Germany

A limit of 6 mg/m^3 is given for fine dust. Man-made mineral fibres less than 1 μm in diameter are listed as compounds that are justifiably suspected of having carcinogenic potential (Deutsche Forschungsgemeinschaft, 1986).

Finland

The 8-h exposure limit for glass- and mineral wool is 10 mg/m^3 (Työsuojeluhallitus, 1981).

France

An 8-h limit value of 10 mg/m^3 is given for mineral wool fibres (Institut National de Recherche et de Sécurité, 1986).

German Democratic Republic

Dust standards in the German Democratic Republic are based on four ranges of free crystalline silica content, assessed in % of weight: over 50% (I); 20–50% (II); 5–20% (III); and under 5% (IV). Exposure limits are specified as MAK_D (average concentration over a workday of 8 h and 45 min) and MAK_K (short-term exposures for periods not exceeding 30 min) in particles/cm^3 (ppcm^3) (International Labour Office, 1980), as follows:

Group	MAK_D	MAK_K
	ppcm³	ppcm³
I	100	300
II	250	500
III	500	1000
IV	800	1500

Italy

For glass- and mineral wool with a quartz content greater than 1%, an exposure limit (L) is calculated for particles between 0.7 and 5 μm, by the counting method:

$$L = \frac{4500}{q+3} \text{ in ppcm}^3,$$

where q = numerical % of quartz particles as determined by the phase-contrast method, or by the gravimetric method:

$$L = \frac{30}{q+3} \text{ in mg/m}^3,$$

where q = % (by weight) of quartz determined as total dust, and

$$L = \frac{10}{q+3} \text{ in mg/m}^3,$$

where q = % (by weight) of quartz determined as respirable dust.

If the quartz content is less than 1%, the exposure limit (by the counting method) is 1500 ppcm³; by the gravimetric method, the exposure limit is 10 mg/m³ for total dust and 3.33 mg/m³ for respirable dust (International Labour Office, 1980).

Norway

For glass and rock/slag fibres, the total dust exposure limit is 5 mg/m³ for an 8-h day (Direktoratet for Arbeidstilsynet, 1981).

Poland

A tentative guideline for an exposure limit for glass- and mineral wool has been established at 4 mg/m³ for an 8-h work shift (International Labour Office, 1980).

Sweden

A limit of 2 fibres/ml for a full working day has been set for glass fibres (synthetic inorganic fibres) (Arbetarskyddsstyrelsen, 1984).

United Kingdom

The long-term exposure limit (8-h time-weighted average) for exposure to man-made mineral fibres is 5 mg/m³, as measured by gravimetric sampling methods for total dust.

A recommended limit of 1 fibre/cm^3 has been agreed for superfine man-made mineral fibres, defined as fibres with a diameter of less than 3 μm and aspect ratios greater than 3:1 (Health and Safety Executive, 1987).

USA

The US Occupational Safety and Health Administration (1986) has established that an employee's exposure to mineral dusts (crystalline quartz) in any 8-h work shift of a 40-h working week should not exceed the 8-h time-weighted average limit calculated by the following formulae:

$$\text{Total dust} = \frac{30 \text{ mg/m}^3}{\% \text{ SiO}_2 + 2}$$

$$\text{Respirable dust} = \frac{10 \text{ mg/m}^3}{\% \text{ SiO}_2 + 2}$$

The American Conference of Governmental Industrial Hygienists (1986) recommends a threshold limit value for mineral wool fibre and fibrous glass dust with less than 1% quartz of 10 mg/m^3 for total dust.

USSR

For glass and mineral fibres, a maximum admissible concentration of 4 mg/m^3 has been set (International Labour office, 1980).

Yugoslavia

The exposure limits established for mineral wool and glasswool are 4 mg/m^3 for respirable dust and 12 mg/m^3 for total dust (International Labour Office, 1980).

2.2 Occurrence

(*a*) *Occupational exposure*

Exposures to man-made mineral fibres are reported as total dust concentrations or respirable fibre concentrations in air. The definitions and methods of measurement of these concentrations are variable (see section 2.3). For respirable fibres, the upper diameter limit is considered to be either 3 μm (Esmen *et al.*, 1978; World Health Organization, 1985) or 3.5 μm (National Institute for Occupational Safety and Health, 1977a).

Strictly, the term 'fibre' should be applied to all particles with a length-to-diameter ratio of $\geqslant$3:1. Aggregates and other morphologically atypical particles that fit these overall dimensions are not considered to be man-made mineral fibres. In most of the tables presented in this section of the monograph, the convention is adopted of reporting only fibres $>$5 μm in length.

(i) *Exposure in production plants*

USA

Williams (1970) reviewed industrial hygiene surveys performed by the Pennsylvania Department of Health in the US fibrous glass industry. The earliest survey was reported in 1944, which was of solvents used in yarn production. Dust measurements were apparently first performed in 1951; surveys were performed in 1947, 1951–1954, 1962, 1964 and 1967 to evaluate in particular exposures to phenol, formaldehyde, noise, hydrogen, fluoride, styrene, methyl methacrylate and dust. [The Working Group noted that reporting of dust measurements as millions of particles per cubic foot (mppcf) of air after impinger collection and light microscopic counting precluded later conversion to total dust, respirable dust or fibres/cm^3 as indices of exposure.]

Johnson *et al.* (1969) took measurements in four facilities producing fibrous glass insulation and in one producing fibrous glass textile products. Table 13 gives total dust and respirable dust concentrations in these facilities; in this study, respirable fibres were defined

Table 13. Dust concentrations (mg/m^3) by plant and operation in fibrous glass production plants in the USA[a]

Operation	Plant no.[b]	Total dust		Respirable dust (<5 μm)	
		Mean	Range	Mean	Range
Batch and marble	1	–	–	–	–
	2	–	–	–	–
	3	1.34	0.18–5.96	0.15	<0.01–0.31
	4	12.29	2.69–21.89	0.55	0.06–1.03
	1–4[c]	6.82	0.18–21.89	0.35	<0.01–1.03
	5	0.12	0.12	0.36	0.19–0.52
Forming	1	0.20	<0.01–0.94	0.03	<0.01–0.24
	2	0.44	0.04–1.70	0.05	<0.01–0.20
	3	0.18	<0.01–0.66	0.07	<0.01–0.45
	4	0.46	0.04–1.74	0.09	<0.01–0.47
	1-4[c]	0.32	<0.01–1.74	0.06	<0.01–0.47
	5	0.06	0.04–0.22	0.05	<0.01–0.36
Spinning and twisting	5	0.11	<0.01–0.40	0.10	<0.01–0.65
Waste recovery	5	0.16	<0.01–0.48	0.12	<0.01–0.73

[a] From Johnson *et al.* (1969)

[b] Plants 1-4 are insulation plants; plant 5 is a textile plant.

[c] Composite results for plants 1-4

as those having diameters <5 μm. Table 14 displays measured concentrations of respirable fibres. [The Working Group considered that these measurements are probably indicative of exposure of US production workers in the 1960s.] The authors concluded that 'the results in terms of airborne concentrations of glass fibres and total dust would indicate that the

Table 14. Fibre concentrations (fibres/cm³; including fibres <5 μm in diameter) by plant and operation in fibrous glass production plants in the USA[a]

Operation	Plant no.[b]	Total fibres		Fibres longer than 5 μm		Fibres longer than 10 μm	
		Mean	Range	Mean	Range	Mean	Range
Batch and marble	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[c]	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[c]	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 and twisting and waste recovery	5	0.72	0.03–12.67	0.11	0–1.97	0.01	0–0.06

[a] From Johnson *et al.* (1969)

[b] Plants 1-4 are insulation plants; plant 5 is a textile plant.

[c] Composite results for plants 1-4

workmen's exposure to these materials is negligible', noting that fibre concentrations in the asbestos textile industry were about 20-fold higher. The judgement that exposures were low was again expressed in 1974 in a review of work practices and controls for the US National Institute for Occupational Safety and Health (Schneider & Pifer, 1974).

The largest body of data on exposure of US production workers was collected as part of an epidemiological study of the industry (Esmen *et al.*, 1979a), which encompassed 16 glasswool, glass filament, rockwool and slagwool plants. Table 15 indicates the type of fibre produced, the number of samples collected and the average nominal fibre size in each facility; Table 16 describes the plant operations that were used to classify jobs in this study; Table 17 shows the concentrations of total suspended particulate matter by type of operation performed; and Table 18 is a summary of fibre concentrations in these facilities. There were large differences in the amounts of total suspended particulate matter, expressed as mg/m³, and of airborne fibres, expressed as fibres/cm³, in different plants and between areas of the same plant. There was also wide variation in these parameters in the same area of the same plant: during production of fibres of nominal diameter >6 μm, ≤40% of airborne fibres were respirable; during the production of fibres of nominal diameter <3 μm, 50–90% of airborne fibres were respirable.

Table 15. Characteristics of 16 facilities in the USA surveyed by Esmen *et al.* (1979a)

Plant no.	Type of fibre produced	Material	No. of dust samples	Average nominal diameter (μm)
1	Loose and continuous	Glass	97	1–12
2	Loose	Slag	55	6
3	Loose	Glass	70	3–6
4	Loose and mixed	Glass	90	1–6
5	Loose	Slag	60	8
6	Loose, continuous and mixed	Glass	111	5–15
7	Loose	Rock	63	6
8	Loose	Glass	105	7–10
9	Loose	Glass	89	7–10
10	Continuous	Glass	97	6–16
11	Loose	Slag	66	7
12	Loose, continuous and mixed	Glass	225	6–115
13	Loose	Rock and slag	72	7
14	Continuous	Glass	84	6–13
15	Loose	Glass	79	0.05–1.6
16	Loose	Glass	90	6–10

Table 16. Plant operations upon which the grouping of data in Tables 17, 18 and 20 were based[a]

Classification	Description
Forming	All hot-end workers, cupola operators, batch mixers, transfer operators, charging operators
Production	Cold-end workers in direct contact with fibres but not involved in cutting, sawing, sanding or finishing operations; workers such as bailers, stuffing operators, machine tenders
Manufacturing	Workers involved in general manufacturing operations, such as trimming, sawing, cutting, finishing, painting finished boards, moulding-drier ovens, handling boxed and/or packaged materials
Maintenance	Maintenance workers who repair production machinery and do general work in the production area, including sweeping floors, cleaning dust collecters and machinery, general cleaning within the plant
Quality control	Workers who sample the product and ascertain product quality
Shipping	Transportation of packaged material, fork-truck operators, shipping-yard operators

[a]From Esmen *et al.* (1979a)

Table 17. Concentrations of total suspended particulate matter (mg/m³) in 16 facilities in the USA[a]

Plant	Forming		Production		Manufacturing		Maintenance		Quality control		Shipping		Overall	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	0.47	0.47	1.04	1.34	0.96	0.96	0.71	0.45	0.21	0.12	0.39	0.09	0.89	1.12
2	1.65	1.17	2.53	2.30	2.28	1.51	2.05	1.32	1.53	0.63	1.34	0.58	1.94	1.68
3	–	–	0.51	0.30	–	–	0.83	0.61	–	–	0.70	0.42	0.65	0.46
4	1.22	0.51	0.77	0.49	1.23	0.95	2.08	4.40	0.52	0.14	1.32	0.96	1.24	2.26
5	0.76	0.25	0.67	1.52	0.29	1.25	0.55	0.32	0.09	–	0.62	0.33	0.60	1.04
6	1.30	0.71	1.77	2.23	0.51	0.39	2.00	2.50	0.49	0.82	0.45	0.19	1.17	1.72
7	2.18	1.62	2.05	0.31	4.31	4.03	6.72	7.84	–	–	1.77	1.02	4.00	4.27
8	–	–	8.48	9.02	1.17	0.55	4.64	8.28	–	–	0.84	0.67	4.73	8.69
9	1.18	0.48	1.90	1.52	1.14	0.53	1.33	0.57	–	–	1.08	0.46	1.33	1.02
10	2.45	0.93	0.75	0.47	0.73	0.33	1.25	1.07	0.32	0.09	0.69	0.15	1.07	0.91
11	2.18	1.64	1.08	1.82	0.87	0.46	1.26	0.49	1.25	–	1.04	0.41	1.37	1.09
12	0.34	0.35	0.20	0.30	0.28	0.26	0.53	0.26	0.53	0.66	0.88	0.08	0.21	0.16
13	4.10	–	1.34	0.46	1.19	1.08	1.80	1.69	–	–	1.31	0.59	1.4	1.08
14	3.00	1.37	0.85	0.59	1.06	0.47	1.57	1.41	–	–	0.91	0.72	1.42	1.21
15	0.30	0.21	0.61	0.51	1.08	0.80	1.09	0.75	1.66	0.73	0.54	0.18	0.75	0.67
16	0.77	0.46	0.82	0.69	0.86	0.52	1.79	1.50	0.44	–	0.76	0.53	1.07	1.02

[a]From Esmen *et al.* (1979a)

Table 18. Concentrations (fibres/cm^3) of airborne fibres, as determined by optical microscopy, in 16 facilities in the USA[a]

Plant	Forming		Production		Manufacturing		Maintenance		Quality control		Shipping		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	0.008	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	0.35
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

[a]From Esmen *et al.* (1979a)

The cumulative distribution of measured concentrations of fibres for each of the 16 facilities is shown in Table 19. The distribution of fibre diameters, as determined by transmission electron microscopy, is shown in Figure 1. A relationship was found between measured average exposures and the nominal diameter of fibre manufactured (Fig. 2). The concentrations of fibres <1 μm, determined by transmission electron microscopy, are shown in Table 20. It can be seen from Tables 18 and 20 that, unlike the situation in asbestos production facilities where fibre counts made by electron microscopy are many times higher than those made by optical microscopy, the fibre concentrations determined by optical and electron microscopy of samples collected in man-made mineral fibre facilities are, with few exceptions, roughly comparable.

Table 19. Distribution of measured average employee exposure to fibres, expressed as cumulative percentage of samples less than stated concentrations, in 16 facilities in the USA[a]

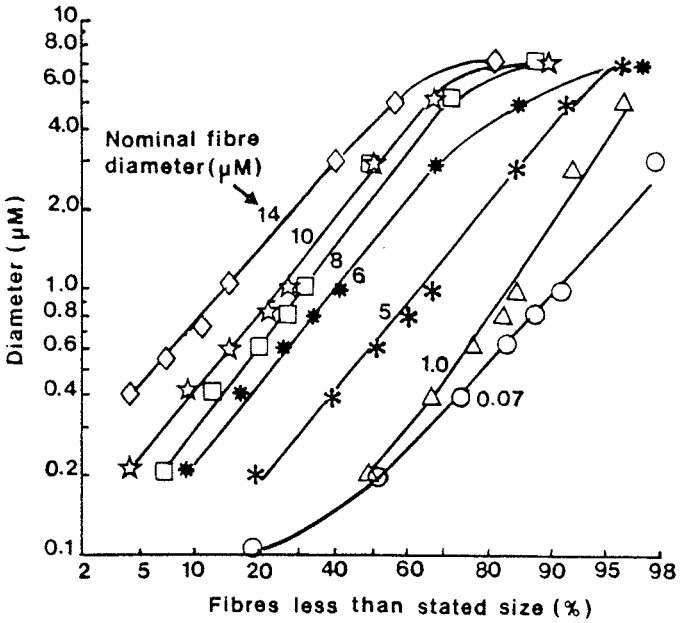
Plant	Average concentration (fibres/cm³)										
	≤0.005	≤0.01	≤0.05	≤0.1	≤0.5	≤1	≤1.5	≤2	≤5	≤10	≤20
1	6.1	11.2	72.4	83.7	98.0	98.0	99.0	100			
2	0	0	32.7	63.6	96.4	100					
3	40.8	50.7	87.3	95.8	97.2	100					
4	6.7	27.8	78.9	93.3	100						
5	3.3	13.1	91.8	98.4	100						
6	47.7	76.6	97.3	98.2	100						
7	0	0	3.2	14.3	81.0	92.1	100				
8	17.1	40.0	89.5	99.0	100						
9	16.7	42.2	95.5	98.9	100						
10	82.5	97.9	100								
11	3.9	13.7	66.7	84.3	100						
12	33.2	65.4	98.6	99.1	100						
13	1.3	6.3	60.8	75.9	97.5	100					
14	6.0	27.7	89.2	97.6	98.8	100					
15	0	0	9.3	28.0	69.3	81.3	89.3	93.3	97.3	98.6	100
16	7.8	20.0	87.8	94.4	98.9	100					

[a]From Corn (1979); samples analysed by phase-contrast microscopy, including fibres ≤3 μm in diameter

The data in Tables 17–20 are based on personal samples taken from within the breathing zones of employees, generally over 7–8 h. The limit of detection for the phase-contrast microscopic evaluations was about 0.0012 fibre/cm³; that for fibre detection by transmission electron microscopy was 0.0023 fibre/cm³, based on an approximately 8-h personal sample collected at a flow rate of 2.0 l/min (Esmen *et al.*, 1979a).

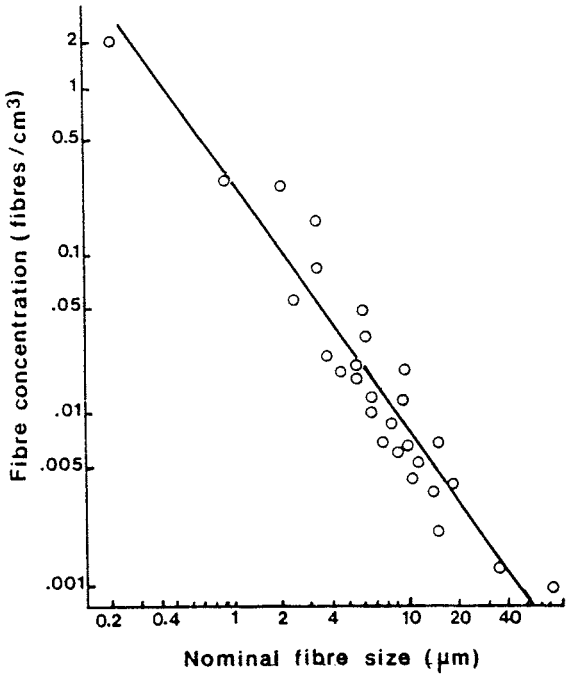
The measurements reported indicate fibre concentrations in the range of 0.1–0.3 fibre/cm³ >5 μm in length (Esmen *et al.*, 1979a). These results can be compared to earlier measurements of exposure to fibres during the manufacture of glass fibre (Williams, 1970).

Fig. 1. Distribution of diameters of airborne fibres[a]



[a]From Esmen *et al.* (1979a), expressed as cumulative % of fibres less than stated size measured during production of fibres of different nominal diameter

Fig. 2. Relationship between measured average exposures (fibres/m^3 determined by phase-contrast microscopy) and nominal diameter of manufactured fibre[a]



[a]From Esmen *et al.* (1979a); each point represents the average concentration of fibres calculated from all samples collected in a plant production unit or in an entire facility producing the nominal fibre size indicated.

Table 20. Concentration (fibres/cm³) of fibres <1 μm in diameter in 16 facilities in the USA[a]

Plant[b]	Forming		Production		Manufacturing		Maintenance		Quality control		Shipping		Overall	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1	0.002	0.001	0.73	2.3	0.01	0.007	0.01	0.03	0.45	0.76	0.002	0.002	0.004	0.17
2	0.04	0.03	0.04	0.02	0.03	0.03	0.04	0.04	0.07	0.08	0.01	0.01	0.04	0.03
3	–	–	0.03	0.03	–	–	0.20	0.71	–	–	0.005	0.003	0.08	0.42
4	0.01	0.005	0.19	0.29	0.12	0.42	0.02	0.02	0.02	0.01	0.009	0.005	0.10	0.28
5	0.01	0.01	0.01	0.007	0.004	0.002	0.01	0.005	0.02	–	0.01	0.002	0.01	0.01
6	0.002	0.001	0.004	0.004	0.004	0.003	0.008	0.03	0.007	0.01	0.004	0.004	0.005	0.02
8	–	–	0.05	0.04	0.02	0.01	0.02	0.02	–	–	0.02	0.01	0.03	0.03
10	0.003	0.002	0.003	0.002	0.004	0.002	0.01	0.01	0.002	0.002	0.002	0.002	0.004	0.007
11	0.12	0.09	0.02	0.02	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.06
12	0.006	0.005	0.004	0.005	0.003	0.003	0.002	0.001	0.005	0.004	0.003	0.001	0.003	0.004
13	0.04	–	0.03	0.03	0.03	0.04	0.02	0.02	–	–	0.01	0.01	0.02	0.04
15	2.0	2.6	6.49	9.37	5.25	14.6	1.3	2.2	12.0	5.83	0.58	0.38	4.4	9.9
16	0.03	0.02	0.04	0.03	0.07	0.04	0.22	0.84	0.03	–	0.01	0.007	0.01	0.04

[a]From Esmen *et al.* (1979a)

[b]Transmission electron microscopic data are not reported for facilities 7, 9 and 14 because the analytical method used was less reliable than that at other plants.

These figures and the results in Table 14, obtained by optical (not phase-contrast) microscopy, suggest that concentrations of airborne fibres decreased somewhat during the period 1969–1979. On the basis of airborne concentrations of respirable dust, approximately 80% of the US facilities had <1 mg/m³ respirable dust and 80% had <5 mg/m³ total dust. It was demonstrated that airborne fibre concentrations, expressed as fibres/cm³, could not be predicted on the basis of total suspended particulate matter concentrations, expressed as mg/m³ (Corn, 1979; Esmen *et al.*, 1979a).

In general, concentrations in US rockwool and slagwool facilities were higher than those in fibrous glass facilities. In two plants, approximately 50–90% of fibres measured in collected samples of airborne particulate matter were <3 μm in diameter (by phase-contrast microscopy), and approximately 60–90% were longer than 10 μm. Average airborne fibre concentrations varied from 0.01 to 0.43 fibre/cm³ in one plant producing slagwool and from 0.20 to 1.4 fibres/cm³ in one producing rockwool; individual plant areas differed widely in airborne fibre concentration. Total airborne particulate matter averaged 0.05–6.88 mg/m³ in the slagwool plant and 0.5–23.6 mg/m³ in the rockwool plant. Thus, there were higher levels of total suspended particulate matter in rockwool and slagwool facilities than in glasswool facilities, although there were large differences between plants (Table 21) (Corn *et al.*, 1976).

Table 21. Concentrations (fibres/cm³) of total fibres in one rockwool and one slagwool production plant in the USA[a]

Dust zone	No. of samples	Total fibres (fibres/cm³)	
		Average	Range
Rockwool			
Warehouse	3	1.4	1.1–1.7
Mixing-Fourdrinier ovens	3	0.14	0.13–0.18
Panel finishing	12	0.40	0.13–1.3
Figre 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
Slagwool			
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

[a]From Corn *et al.* (1976); as determined by phase-contrast microscopy

Fibre concentrations during ceramic-fibre production in the USA were higher than those in glasswool and continuous glass filament facilities, but were comparable with exposures to airborne fibres in rockwool and slagwool facilities. The individual plants displayed wide differences (Table 22), and the correlation between total suspended particulate matter, expressed as mg/m^3, and total fibre exposures, expressed as fibres/cm^3, was not good. Approximately 90% of airborne fibres in the three facilities were determined to be respirable, i.e., <3 μm in diameter, and approximately 95% were <50 μm in length.

Table 22. Airborne concentrations of total and respirable fibres in three ceramic fibre production plants in the USA[a]

Dust zone	Total respirable fibres[b] (fibres/cm^3)	Total fibres[b] (fibres/cm^3)	Total fibres[c] (fibres/cm^3)	Respirable fraction[d]
Plant A (all)	2.6	3.3	2.6	0.79
Finishing	2.1	2.6	1.9	0.82
CVF[e]	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[f]	6.9	8.7	7.6	0.79
Maintenance	0.50	0.64	0.52	0.79
GFA[g]	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 (all)	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 (all)	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	0.02	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

[a] From Esmen *et al.* (1979b)

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

[c] As determined by optical microscopy only

[d] Total respirable concentration/total fibre concentration

[e] CVF, bulk fibre mixed with colloidal silica and vacuum formed

[f] OEM, some products from CVF trimmed with hand saws, drilled and packaged

[g] GFA, blankets from line 2 cut by hand into specific shapes

There were variations in the percentage of respirable fibres and fibre dimensions, depending on the plant and individual plant operations, with a range of respirable fibres of 71–96% (Esmen *et al.*, 1979b).

Europe

In 1977–1980, scientists at the Institute of Occupational Medicine (Edinburgh, UK) studied 13 European plants, of which six produced rockwool, four, glasswool and three, glass filaments (Ottery *et al.*, 1984). The measurements in this study form the basis for the exposure in the study of Saracci *et al.* (1984a,b), discussed in section 3.3. At each factory, the work force was classified into occupational groups on the basis of job and work zone, and a proportion of each group was selected at random for personal sampling. A total of 1078 samples were taken for counting respirable fibres at rockwool and glasswool plants, generally over 7–8 h. The respirable fibre concentrations given in the original reports were too low by a factor of about two, and were thus reassessed (Cherrie *et al.*, 1986). Tables 23 and 24 present the revised concentrations for the glasswool and rockwool plants; only unrevised figures from the study by Ottery *et al.* (1984) are available for the three continuous filament plants (Table 25).

The range of group arithmetic means in the four glasswool plants was 0.01–0.16 fibre/cm^3, but up to 1.0 fibre/cm^3 was found when the manufacture of special fine-fibre ear plugs was included. In the rockwool plants, the combined arithmetic means for occupational groups were 0.01–0.67 fibre/cm^3. Concentrations of respirable fibres in the continuous glass filament plants were very low: occupational group means ranged from 0.001 to 0.023 fibre/cm^3 (Cherrie *et al.*, 1986).

The median fibre lengths were within the range 8-15 μm for the glasswool plants and 10-20 μm for the rockwool plants. Median fibre diameters ranged from 0.7–1 μm for glasswool plants and 1.2–2 μm for rockwool (Cherrie *et al.*, 1986). The size distribution in two Danish rockwool plants is given in Table 26. A linear regression analysis of log diameter *versus* log length for airborne fibres gave a correlation coefficient ranging from 0.48 to 0.67 for rockwool production and use and for glasswool use, implying that the longer the fibres were, the larger (on average) were their diameters (Schneider *et al.*, 1985).

An experimental simulation of a rockwool production process with conditions similar to those operating in the 1940s was carried out at a Danish pilot plant to determine the effect on airborne fibre concentrations of addition of oil to the rockwools. The time-weighted average concentrations of respirable fibres, as measured by personal sampling, were about 1.5 fibres/cm^3 with oil and about 5 fibres/cm^3 without addition of oil; the concentrations of inspirable dust were about 6 mg/m^3 and 100 mg/m^3, respectively. There was no substantial difference in airborne fibre concentration when simulated batch-produced wool and continuously-produced wool were handled (Cherrie *et al.*, 1987).

The National Swedish Board of Occupational Safety and Health (Arbetarskyddsstyrelsen, 1981) took measurements in all the Swedish glass- and rockwool plants. The results, which were not included in the Institute of Occupational Medicine survey, are shown in Table 27.

Table 23. Fibre concentrations (fibres/cm³)[a] in combined occupational groups in four European glasswool plants (1977-1980)[b]

Combined occupational group	Plant 7			Plant 2			Plant 6			Plant 10		
	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range
Preproduction	5	0.01	0.02–0.01	8	0.01	<0.01–0.01	5	0.01	0.01	5	0.01	<0.01–0.03
Production	39	0.05	0.01–0.62	26	0.01	<0.01–0.03	27	0.03	0.01–0.11	61	0.05	<0.01–0.22
Maintenance	20	0.07	0.01–0.06	4	0.03	0.01–0.06	12	0.04	<0.01–0.17	27	0.02	<0.01–0.06
General	15	0.03	0.01–0.06	10	0.02	0.01–0.04	10	0.02	0.01–0.04	12	0.03	<0.01–0.06
Secondary process 1	37	0.04	0.01–0.11	32	0.05	0.01–0.21	26	0.03	<0.01–0.07	36	0.02	<0.01–0.06
Secondary process 2	23	1.00	0.17–4.02	–			2	0.07	0.05–0.09	45	0.16	0.02–1.39
Cleaning	–			–			4	0.01	0.01–0.02	–		
Overall mean[c]		0.2			0.02			0.03			0.05	
Plant mean and range (mg/cm³)[d]	124	1.3	0.2–21	69	0.6	0.1–2.7	79	1.2	0.1–20	168	1.3	0.15–21

[a]Including fibres ⩽3 μm in diameter

[b]From Cherrie *et al.* (1986)

[c]Computed by the Working Group as average over occupational group mean

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

Table 24. Fibre concentrations (fibres/cm³)[a] in combined occupational groups in six European rockwool plants (1977-1980)[b]

Combined occupational group	Plant 1			Plant 5			Plant 4			Plant 3			Plant 8			Plant 9		
	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range
Preproduction	8	0.08	0.01–0.22	2	0.01	0.01	7	0.03	0.01–0.07	3	0.06	0.03–0.11	1	0.04	0.04	4	0.01	<0.01–0.01
Production	36	0.10	0.02–0.37	22	0.06	0.02–0.14	27	0.06	0.02–0.19	28	0.12	0.03–0.32	19	0.05	0.01–0.13	51	0.05	0.01-0.16
Maintenance	9	0.08	0.05–0.18	12	0.05	0.01–0.14	20	0.05	0.02–0.12	8	0.05	0.03–0.10	9	0.03	0.01–0.07	10	0.04	0.01–0.11
General	16	0.08	0.02–0.37	7	0.04	0.03–0.07	13	0.06	0.02–0.09	8	0.07	0.04–0.14	2	0.04	0.04	23	0.06	0.01–0.36
Secondary process 1	32	0.10	0.03–0.21	16	0.07	0.01–0.15	28	0.08	0.03–0.33	11	0.12	0.06–0.23	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	–			5	0.09	0.04–0.11	8	0.06	0.02–0.14	4	0.13	0.05–0.29	8	0.09	0.01–0.18	12	0.14	0.02–0.44
Overall mean[c]		0.14			0.05			0.06			0.13			0.08			0.15	
Plant mean and range (mg/m³)[d]	101	2.3	0.3–26	53	1.0	0.2–4.7	86	1.1	0.3–3.5	56	1.6	0.4–4.0	60	1.0	0.06–2.3	164	0.7	0.03–4.0

[a]Including fibres ≤3 μm in diameter

[b]From Cherrie *et al.* (1986)

[c]Computed by the Working Group as average over occupational group mean

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

Table 25. Fibre concentrations (fibres/cm³)[a] in combined occupational groups at three European continuous glass filament plants (1977–1980)[b]

Combined occupational group	Plant E			Plant J			Plant N		
	No.	Mean	Range	No.	Mean	Range	No.	Mean	Range
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	–			–		
Plant mean and range (mg/m³)	145	1.4	0.1–38	132	0.6	0.03–2.7	115	0.9	0.1–2.7

[a] Including fibres ≤3 μm in diameter

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

Table 26. Fibre distributions of glasswool and rockwool in two Danish rockwool plants[a]

Site	No. of samples	Diameter		Length	
		Geometric mean (μm)	Geometric SD	Geometric mean (μm)	Geometric SD
Rockwool plant A	6	0.95	3.1	13	3.4
Rockwool plant B	38	0.99	3.3	14	3.6
Rockwool, special fibres	6	1.46	2.8	27	3.3
Rockwool, conventional fibres	28	1.73	2.4	22	3.1
Use of rockwool	21	1.20	2.7	22	4.0
Use of glasswool	8	0.75	2.8	16	3.5

[a] From Schneider *et al.* (1985)

The sampling strategy was machine- and not person-oriented, and the aim was to sample at least one person exposed to man-made mineral fibres for each job, machine type and production line. [The Working Group considered that the finding of fibre levels higher than any of those found by the Institute of Occupational Medicine may have been due to the sampling strategy.] The parameters of some selected size distributions in the Swedish measurements were comparable with the values in Table 26 (Krantz & Tillman, 1983).

Table 27. Respirable fibre concentrations (fibres/cm³) in glasswool and rockwool production plants in Sweden (1978-1981)[a]

Combined occupational group	Three rockwool plants			Two glasswool plants		
	No.	Mean	Range	No.	Mean	Range
Production	90	0.20	0.051–1.9	49	0.22	0.056–0.65
Maintenance	64	0.21	0.031–1.2	89	0.36	0.037–5.3
General	45	0.15	0.031–0.34	34	0.19	0.034–0.53
Secondary process 1	35	0.23	0.058–0.52	59	0.19	0.038–0.73
Secondary process 2	2	0.21	0.15–0.27	5	0.13	0.083–0.16
Cleaning	105	0.32	0.025–2.6	76	0.21	0.026–1.0
Miscellaneous	19	0.20	0.031–0.66	15	0.11	0.014–0.49
Overall mean[b]		0.22			0.20	

[a]Including fibres ⩽3 μm in diameter; arithmetic means and ranges were computed by the Working Group from data on individual samples taken from the Swedish reports (Arbetarskyddsstyrelsen, 1981).

[b]Computed by the Working Group as average over occuaptional group mean

In a survey of glasswool, rock-/slagwool and ceramic fibre plants carried out by the Factory Inspectorate in the UK, separate samples were taken for fibre counting and for gravimetric determination. Overall duration of sampling was chosen to be representative of the process or operation and not 8-h averages; continuous, full-shift processes were usually monitored for at least 4 h. The overall plant means are shown in Table 28. The percentage of fibres ⩽3μm was 60–80% (Head & Wagg, 1980). [The Working Group considered that the finding of both total dust and fibre concentrations several times higher than in the study of the Institute of Occupational Medicine may have been due to differences in sampling strategy.]

Table 28. Concentrations of total airborne dust and respirable fibres in insulation wool production plants in the UK (period not stated)[a]

Fibre type	Mean total dust			Mean respirable fibre		
	No. of samples	Concentration (mg/m³)	Range	No. of samples	Concentration (fibres/cm³)[b]	Range
Glass fibre	32	11.1	0.7–78.2	50	0.31	0.02–1.10
Glass fibre	16	4.1	0.5–14.3	35	0.27	0.01–0.79
Glass fibre	30	8.9	0.4–51.3	67	0.12	0.003–0.85
Rock-/slagwool	22	6.5	0.7–16.2	55	0.89	0.03–10.3
Ceramic fibre	16	8.3	0.2–26.3	45	1.27	0.06–6.14
Alumina fibre	15	4.9	0.3–13.4	33	1.09	0.03–5.82

[a]From Head & Wagg (1980)

[b]Including fibres ⩽3 μm in diameter

In the same survey, breathing zone and static samples taken during the manufacture of woven and nonwoven glass fibre mats contained 0.3–1.7 mg/m^3 total dust (23 samples); the mean concentration of total fibres ranged from 0.007 to 0.15 fibre/cm^3 (36 samples). Individual samples reached 0.65 fibre/cm^3, but only 0.009 fibre/cm^3 were ≤ 3 μm in diameter. The overall percentage of fibres ≤ 3 μm in diameter was 8% for one and <1% for the other of the two plants under study (Head & Wagg, 1980).

In two French glasswool plants, the concentration of total dust was 1.0–3.4 mg/m^3 and that of fibres <3 μm diameter was 0.05–0.18 fibre/cm^3. The geometric mean fibre lengths were 2.8 and 3.4 μm and the geometric mean diameters, 0.26 and 0.27 μm, in the two plants, respectively. A magnification of at least 5000× was used, and all measurements were made on photomicrographs (Kauffer & Vigneron, 1987). The study of Ottery *et al.* (1984) and the Swedish (Krantz & Tillman, 1983) and Danish (Schneider *et al.*, 1985) studies were based on elemental analyses, and measurements were made directly on the screen using a magnification of 2000–5000×. [The Working Group noted that use of photomicrographs gives improved results but precludes analysis of fibres other than man-made mineral fibres.]

(ii) *Exposures to compounds other than man-made mineral fibres in production plants*

The technical history of each of the factories in the European study has revealed a variety of other exposures, but, as these were historical, they could not be quantified. Asbestos was used in all factories by a small number of persons for personal protection and thermal insulation. In four factories, asbestos had been used mostly as sticking yarn [estimated exposure, <1 fibre/cm^3] and cloth [estimated exposure, <10 fibres/cm^3]. Furthermore, loose asbestos may have been handled on an experimental basis. In one plant, olivine was used, which is potentially contaminated with natural mineral fibres with a composition similar to tremolite; the probable average exposure in the preproduction area was estimated to have been 0.1 fibre/cm^3 (Cherrie & Dodgson, 1986).

Exposure to polycyclic aromatic hydrocarbons may have occurred close to the cupola furnaces in three rockwool and in one glasswool plants and in one using an electric furnace. The possibility of exposure to arsenic from copper slags is also mentioned (Cherrie & Dodgson, 1986). In one of the plants in the IARC study (Saracci *et al.*, 1984a,b), situated in the Federal Republic of Germany, exposures to coal-tar, bitumen, quartz and asbestos have been identified, but not quantified (Grimm, 1983).

Other airborne toxic contaminants have been measured in US man-made mineral fibre plants, including several potentially carcinogenic contaminants, which were measured in areas and in personal breathing zones at selected locations where exposures were likely to occur: asbestos, <0.02–7.5 fibres/cm^3; arsenic, 0.01–0.48 μg/m^3; chromium (insoluble), <0.002–0.036 mg/m^3; benzene-soluble organics, 0.012–0.052 mg/m^3; formaldehyde, 0.03–20 ppm (0.04–24.4 mg/m^3); silica (respirable), 0.004–0.71 mg/m^3; and cristobalite (respirable), 0.1–0.25 mg/m^3 (Manville, CertainTeed and Owens-Corning Fiberglas Companies, 1962–1987). The range of concentrations was similar to that found in one or more of the plants included in the major US epidemiological study (Enterline *et al.*, 1983; Enterline & Marsh, 1984; Enterline *et al.*, 1987). [The Working Group noted that air

sampling records for these plants were obtained periodically, rather than systematically, during the years 1962–1987. It is not possible to derive defensible long-term average exposure estimates from these records. The measured personal exposures are cited only to corroborate the presence of other carcinogens in the environment of selected man-made mineral fibre production workers.]

(iii) *Exposure during use*

The work environment of US insulating workers was described in 1971 when the major concern was asbestos; however, exposure to man-made mineral fibres, in particular fibrous glass, was also addressed (Table 29; Fowler *et al.*, 1971). More recently, measurements have been made of exposures during production of aircraft insulation and installation of duct insulation, acoustical ceilings, attic insulation (blowing fibrous glass and mineral wool), building insulation (blankets and batts) and duct systems (Table 30; Esmen *et al.*, 1982). The results indicate that exposures of users may exceed those of production workers.

Table 29. Concentrations and dimensions of airborne fibres from various operations using fibrous glass insulation[a]

Operation	Parent material (mean fibre diameter, μm)	Breathing zone air samples	
		Fibres/cm³	Mean fibre diameter (μm)
Duct wrapping	5.3	1.26	4.7
	6.3	0.90	4.0
	6.4		
	4.0	0.51	3.4
		0.79	3.6
	4.1	1.40	2.6
		1.33	2.3
	7.5	0.80	2.5
	5.8	1.20	6.2
	5.5	2.34	5.0
	7.2	0.53	7.4
Wall and plenum insulation	10.2	3.26	8.4
	8.1	4.18	3.5
	7.6		
	7.8	8.08	3.8
	8.1		
Pipe insulation	8.5	0.93	3.1
		0.48	4.1
	6.7	0.57	3.4
	6.0		
	6.0		
	5.6		
Fan housing insulation	6.9	1.57	3.5

[a]From Fowler *et al.* (1971)

Table 30. Airborne concentrations of respirable fibres[a] in the final preparation and installation of man-made mineral fibre insulation, as determined by a combination of phase-contrast and electron microscopic techniques[b]

Product and job classification	No. of samples	Fibre concentration (fibres/cm³)		
		Average	Range	Average respirable fractions[c]
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				
Fibrous glass				
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
Mineral 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
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
Isolated jobs	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
Isolated jobs	3	0.05	0.012–0.076	0.94
Fibrous glass 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

[a] $\leqslant 3$ μm in diameter

[b] From Esmen *et al.* (1982)

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

In construction work, the time spent in active use of man-made mineral fibres may vary widely. In the USA, the typical work day of an insulation installer included about 4 h of actual installation (Esmen *et al.*, 1982). The exposure pattern of members of the joiners' and carpenters' union in Denmark was determined by means of questionnaires; 60% of members spent 0.5–15% of their working hours per month using man-made mineral fibres (Schneider, 1984).

During blowing of rock-/slagwool, exposure to fibres ≥1 μm in diameter was 0.035 fibre/cm³ for a worker in a lorry and 0.55 fibre/cm³ for a worker who directed the flow of rock-/slagwool into the house. In another study, the levels were 0.9–1.4 fibres/cm³ for an installer in a house and 0.09–0.24 fibre/cm³ in the lorry. The time-weighted average concentration for all measurements was 0.6 fibre/cm³, as determined by optical microscopy (Zirps *et al.*, 1986). It was stated that a typical work day of an installer included about 4 h exposure to fibres, an estimate also used by Esmen *et al.* (1982).

Large surveys have been made of user industries in the UK and Scandinavia (Schneider, 1979a; Head & Wagg, 1980; Hallin, 1981; Schneider, 1984). The most important is the construction industry, in which a great variety of man-made mineral fibre products are used. [The Working Group noted that full-shift sampling had not been used in these surveys, but the lengths of time sampled were designed to be representative of the particular product or operation being studied. Since total dust concentrations were measured with various sampling heads of different efficiencies, comparisons of total dust concentrations can be only indicative.] The results from the Swedish and Danish surveys are shown in Tables 31 and 32. The distribution of single results for respirable fibre concentrations had geometric means of 0.22 and 0.14 fibre/cm³ and geometric standard deviations of 3.3 and 3.8 in the Swedish and Danish surveys, respectively (Schneider, 1984). Very few results exceeded 2 fibres/cm³. Information on fibre size from the Danish user industry is given in Table 26 (Schneider *et al.*, 1985). The geometric mean respirable fibre concentration was 0.046 fibre/cm³ in open and ventilated spaces and 0.50 fibre/cm³ in confined and poorly-

Table 31. Concentrations of total dust and respirable fibres[a] during insulation in Sweden (1979-1980)[b]

Operation	Total dust (mg/m³)		Respirable fibres/cm³	
	Mean[c]	Range	Mean[c]	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 fabric	4.18	3.6–5.2	0.60	0.30–0.76

[a] ≤3 μm in diameter

[b] From Hallin (1981)

[c] Calculated by the Working Group

Table 32. Concentrations of total dust and respirable fibres[a] during insulation in Denmark[b]

Operation	Total dust (mg/m³)		Respirable fibres/cm³	
	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

[a] <3 μm in diameter

[b] From Schneider (1984)

ventilated spaces (Schneider, 1984). Handling of man-made mineral fibre batts can redisperse gypsum dust from previous installation of gypsum boards, and high concentrations of respirable gypsum fibres have been found: 30 fibres/cm³ (as determined by scanning electron microscope; length >5 μm) and 44 mg/m³ (total dust), as measured over a 30-min period (Schneider, 1979a).

In a UK survey of exposures during insulation, application of loose fill appeared to generate the highest respirable fibre concentrations. The survey also included measurements taken during use of ceramic fibres (Table 33) (Head & Wagg, 1980).

Table 33. Concentrations of total dust and respirable fibres[a] in breathing zone and static samples during insulation and during application of ceramic fibres[b]

Product	Total dust (mg/m³)			Respirable fibres/cm³		
	No. of samples	Mean	Range	No. of samples	Mean	Range
Construction insulation						
Domestic loft						
Blankets	9	35.6	8.2–90	12	0.70	0.24–1.76
Loose fill	4	30.9	5.0–59.7	6	8.19	0.54–20.9
Fire protection	9	16.6	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
Ceramic fibres in manufacture and use of high-temperature insulation and ceramic mouldings	6	1.5	0.7–5.2	11	0.55	0.09–0.87
Alumina fibres in manufacture of stack block insulation and engine silencer insulation	11	10.3	1.5–22.9	30	1.9	0.35–5.64

[a] $\leqslant 3$ μm in diameter

[b] From Head & Wagg (1980)

Levels of total dust and respirable fibres (<3 μm in diameter) during the use of fine-diameter, special-purpose glass fibres in the UK and the USA are summarized in Table 34. In 1980–1983, the UK Factories Inspectorate (1987) surveyed factories where man-made mineral fibres of <3 μm in nominal diameter were used. The concentrations of total dust and airborne fibres are shown in Table 35.

Table 34. Concentrations of total dust and respirable fibres[a] during the use of fine-diameter, special-purpose glass fibres

Exposure	Total dust (mg/m³)			Respirable fibres/cm³			Reference
	No. of samples	Mean	Range	No. of samples	Mean	Range	
Production of glass fibre paper		–			10.1	1.6–44.1[b]	Schneider (1984)
	28	1.1	0.2–4.3	44	1.54	0.09–18.8[c]	Head & Wagg (1980)
Production of air filters	5	0.4	0.07–1.0	34	0.33	0.02–2.55[c]	Head & Wagg (1980)
Aircraft insulation					4.6	0.4–24.4[b]	Schneider (1984)
Aircraft insulation		0.38	0.04–1.49		0.41	0.012–3.78[d]	Schneider (1984)

[a] ≤3 μm in diameter

[b] Total fibre concentration by optical microscopy; average diameter distribution, no less than 89% of fibres <3.8 μm

[c] Phase-contrast optical microscopy

[d] Combined optical and electron microscopy

Table 35. Concentrations of total dust and fibres <3 μm diameter during use of special-purpose fibres[a]

Exposure	Mean concentrations of total dust (mg/m³)	Total fibres/cm³ (mean counts)[b]
Manufacture of glass fibre paper	0.47–2.28	2.9–13
Conversion of glass fibre paper	0.17–0.49	0.53–15.1
Manufacture of refractory fibres	0.83–4.0	0.49–9.2
Use of refractory fibres	–	2.7–17.1

[a] From UK Factories Inspectorate (1987), personal samples

[b] Determined by transmission electron microscopy

Data on the nominal diameter of fibres in old glasswool, rockwool and slagwool can give information about the presence of fine fibres in the original bulk material.

In the Federal Republic of Germany, eight samples of old insulating materials (1947–1963) were compared with five samples of materials produced by modern techniques; small

pieces (1.44 cm^2, 1–4 mm thick) were investigated under a scanning electron microscope. It was concluded that there were some significant differences between specific products regarding the lowest fibre diameters, but no significant difference between old and new products. The fraction of fibres with diameters <1 μm or <3 μm in the old products was comparable to that in the modern ones. The samples represented a broad range of manufacturing methods (Poeschel *et al.*, 1982).

In Denmark, nine rockwool samples from a single manufacturer covering the years 1953–1980 were tested in a dust box by shaking (5 g) of bulk material. Scanning electron microscopic analysis of the generated airborne dust showed a decreasing trend with time for the relative content of thin fibres (<0.25 μm and 0.5 μm in diameter), in particular for the length-weighted diameters (Schneider & Smith, 1984).

During removal of rockwool insulation laid in a loft in 1951, 8-h time-weighted averages in the breathing zone were 9 fibres/cm^3 (average for three workers) and 33 mg/m^3 total dust. No binder or dust suppressant had been used in 1951. Subsequently, new man-made mineral fibre was applied in the same loft, giving 0.5 fibre/cm^3 and 16 mg/m^3. The diameter distribution of the airborne fibres generated during removal of the old product was comparable to that measured during the use of modern products (Schneider, 1979a). Theoretical calculations indicate that not only the nominal diameter but also the diameter distribution of fibres in the bulk material, as well as the ventilation rate, have an effect on the size distribution and concentration of airborne fibres (Schneider *et al.*, 1983).

Ceramic fibres may transform into cristobalite upon heating (Aldred, 1985; Strübel *et al.*, 1986). Workplace exposure measurements during removal of ceramic fibre insulation from high-temperature applications have shown significant exposures to cristobalite (Gantner, 1986).

In the production of reinforced plastics, dust concentrations were 0.001–0.01 total fibre/cm^3 and up to 0.002 respirable fibre/cm^3 (three samples) during glass mat preparation and spray lay-up. Trimming operations were more dusty: the total dust concentration reached 62 mg/m^3 in one plant with apparently poor dust control. The mean total fibre concentration in the plant was 0.28 fibre/cm^3 (range, 0.02–1.43), and the respirable fibre concentration was 0–0.08 fibre/cm^3. In another plant with better dust control, total fibre concentrations were only 0.005–0.06 fibre/cm^3, of which about half were respirable (<3 μm in diameter) (Head & Wagg, 1980).

Mineral fibres may also be produced unintentionally. It has been reported that exposure to silicon carbide fibres may occur during the production of silicon carbide. Fibre levels were less than 1 fibre/cm^3, and the highest short-term average concentration was 5 fibres/cm^3 (as measured by optical microscopy). The geometric mean length was 4.5 μm and the geometric mean diameter, 0.23 μm (as determined by scanning electron microscopy) (Bye *et al.*, 1985).

Table 36 gives an overall summary of estimated fibre concentrations generated during the production and use of man-made mineral fibres, as well as typical levels in nonindustrial environments and outdoor air.

Table 36. Ranges of airborne fibre concentrations in typical exposure situations

Fibre concentration (fibres/cm³)	Location/use	Reference
Ultralow (<0.0001)[a]	Outdoor: rural area Buildings: thermal insulation	Höhr (1985)
Extremely low (0.0001–0.001)[a]	Outdoor: large cities Buildings: ceiling boards Ventilation systems	Höhr (1985) Rindel *et al.* (1987) Balzer (1976)
Very low (0.001–0.01)		
Glass continuous filament	Production and use	Cherrie *et al.* (1986)
Coarse glass fibre	Production and use	
Ceiling boards	Buildings: some damage, some ventilation ducts	Schneider (1986)
Low (0.01–0.1)		
Glasswool	Production and most secondary production	Höhr (1985)
Rockwool	Production and most secondary production	
Rock-/slagwool	Production and most secondary production	
Ceiling boards	Buildings: severe damage	Schneider (1976)
Medium (0.1–1.0)		
Fine glass fibre	Production	Höhr (1985)
Rockwool	Some secondary production and user industry	
Ceramic	Primary production and user industry	
Glasswool	User industry	
High (>1.0)		
Very fine glass fibre	Production and use	
Glass-/rockwool, loose	User industry: blowing into attic	
Glass-/rockwool, without dust suppressants	Production and use	
Ceramic	Secondary production and some user industry	

[a]Estimated from transmission electron microscopic measurements

(*b*) *Ambient air*

In 36 of 300 ambient air samples taken from sites in California, USA, the arithmetic mean of glass fibres/cm³ was 0.0026 (range, nondetectable–0.009), as determined by phase-contrast optical microscopy (for fibres with diameters >2.5 μm) and electron microscopy. The geometric mean diameter was 2.2 μm and length, 16 μm (Balzer, 1976). [The Working Group noted that the detection limit of the electron microscopic method was not stated.]

In the Federal Republic of Germany, fibre concentrations in three large cities and in one rural area (Krahm) were monitored in 1981–1982 (Table 37). Samples were analysed under a transmission electron microscope with energy-dispersive X-ray and electron diffraction analysis after ashing to remove organic material; the total fibre count thus represents only inorganic fibres. The fibres identified as glass constituted less than 1% (Krahm) to 5% (Dortmund) of the total concentration of inorganic fibres and represented 3% (Krahm) to 40% (Dortmund) of the asbestos concentration (Höhr, 1985). [The Working Group estimated from the data that about 25% of the glass fibres had diameters exceeding 0.2 μm and lengths exceeding 5 μm and would thus have been counted by optical phase-contrast microscopy.]

Table 37. Fibre[a] concentrations in ambient air in the Federal Republic of Germany in 1981–1982[b]

Measuring site	No. of samples	Fibre/cm³				Size of glass fibres[c] (μm)	
		Total	Chrysotile	Amphibole	Glass	CMD	CML
Duisburg	17	0.041	0.0022	0.0019	0.00050	0.26	2.54
Dortmund	6	0.036	0.0026	0.0019	0.00170	0.25	3.06
Düsseldorf	21	0.027	0.0014	0.0013	0.00040	0.30	3.64
Krahm (rural area)	9	0.012	0.0005	0.0007	0.00004	0.89	2.76

[a]Not reported in this table are fibres classified as quartz, aluminium, iron, rutile, sulphur or others.

[b]From Höhr (1985)

[c]CMD, count median diameter; CML, count median length

The total fibre dust emission to the environment for the whole of the Federal Republic of Germany from the manufacture of man-made mineral fibres has been estimated at 1.8 tonnes per year. The fibres are mostly coarse, and 350 kg of fibres 8–20 μm in length and only 80 kg of fibres <1 μm in diameter are estimated to be emitted per year (Tiesler, 1983).

(c) *Other exposures*

In the late 1960s, concern was expressed over health problems associated with possible erosion of fibrous glass used to line ventilation and heating ducts. Glass fibres were found in settled dust on walls and permanent structures in buildings (Cholak & Schafer, 1971); and, in the San Francisco Bay area, CA, USA, the glass fibre concentration in 13 ventilation systems was undetectable–0.002 fibre/cm³ in 1968–1971, as determined by combined electron and optical microscopy (geometric mean diameter, 1.3 μm; length, 11 μm). In some cases, there was a decrease in fibre concentration after fibre-containing outdoor air had passed through the air transmission system (Balzer *et al.*, 1971; Balzer, 1976).

Medium-efficiency air-cleaning units most often contain glass fibre filters. Laboratory tests showed that fibre entrainment did not depend on operating velocity and that filter

damage (tears longer than 8 cm) may increase entrainment. The test implied that, after a short initial surge in concentration, the indoor fibre concentration level becomes indistinguishable from the ambient level (assumed to be 0.00007 fibre/cm^3) within one day (Esmen *et al.*, 1980). Gross fibre contamination of a house with a faulty air-conditioning system was reported (Newball & Brahim, 1976).

Fibre concentrations in air in a hospital building in which air ducts were lined with glass fibres were 0.003–0.020 fibre/cm^3. No fibre was found in two rooms in a section where ducts were not lined (National Institute for Occupational Safety and Health, 1980).

Extensive measurements of concentrations of man-made mineral fibres in schools and office buildings have been carried out in Denmark. A random sample of mechanically-ventilated schools, most of which had man-made mineral fibre noise baffles or linings in ducts, showed concentrations of undetectable–0.0001 fibre/cm^3 (Table 38). Under special circumstances, such as after water damage or faulty construction, high concentrations were found, e.g., 0.084 fibre/cm^3, in a nursery school in which the ceilings were covered with man-made mineral fibre boards containing water-soluble binder. In general, concentrations were much lower. The institutions were classified into those in which the ceilings were covered with man-made mineral fibre products with resin or water-soluble binder and those which had no readily visible man-made mineral fibre products. The fibres were identified and counted using phase-contrast light microscopy with polarization (Schneider, 1986; Rindel *et al.*, 1987).

Table 38. Mean dust and fibre concentrations in schools, nursery schools and offices in Denmark[a]

Type of institution[b]	No. of institutions	Respirable man-made mineral fibres (fibre/cm^3)[c]	Nonrespirable man-made mineral fibres (fibre/cm^3)[c]	Other respirable fibres (including organics) (fibre/cm^3)	Other nonrespirable fibres (including organics) (fibre/cm^3)
A (1984)	10	0.0001	0.000 02	0.18	0.013
B (1984)	6	0.0001	0.000 04	0.15	0.011
C (1984)	8	0.000 04	0–0.000 08	0.17	0.012
D (not stated)		0.000 07	–	0.017	0.0007

[a]From Schneider (1986); Rindel *et al.* (1987)

[b]A, ceilings made of man-made mineral fibre with water-soluble binder; B, ceilings made of man-made mineral fibre with resin binder; C, without readily visible man-made mineral fibre products; D, mechanically-ventilated schools

[c]Several results were below the detection limit of 0.000 04–0.000 08 fibre/cm^3 and were calculated using statistical procedures

Detection of man-made mineral fibres on surfaces can indicate the presence of such fibres in the indoor environment (Schneider, 1986; Rindel *et al.*, 1987). Concentrations in nursery schools on surfaces that were not cleaned regularly ranged typically from 0.3 to 4.5 nonrespirable man-made mineral fibres/cm^2 but reached 760 respirable fibres/cm^2 and 1160 nonrespirable fibres/cm^2; the presence of fibres on fingers was also demonstrated

(Schneider, 1986). Fibres have been found in the eyes of office workers (Alsbirk *et al.*, 1983) and of man-made mineral fibre production workers (Schneider & Stockholm, 1981).

Filtering facepiece respirators may have a filter medium containing super-fine man-made mineral fibres. It has been reported that these respirators may release fibres during use (Howie *et al.*, 1986). During laundering, fibrous glass textiles may contaminate other clothing with which they are washed (Lucas, 1976).

2.3 Analysis

Optical microscopy, electron microscopy and gravimetry are the methods most commonly used for measuring man-made mineral fibres in air. Methods of sampling and of optical and scanning electron microscopy have improved with time. The World Health Organization (1985) has proposed reference methods.

Dust samples are collected by drawing a measured quantity of air through a filter. Mass and fibre concentrations have been determined from separate samples (Schneider, 1979a; Head & Wagg, 1980), and from single samples used in turn for weighing and particle counting (Esmen *et al.*, 1979b; Hallin, 1981; Ottery *et al.*, 1984). Usually, separate samples are taken for electron microscopy (Schneider, 1979a; Ottery *et al.*, 1984). Fibre counting requires that the dust be uniformly distributed across the filter, and therefore open-faced filters are used. If the same sample is also used for gravimetric determination, sampling efficiency may not conform to the definition of total dust or inspirability. Settled dusts are sampled from surfaces or from the skin using sticky foils (Cholak & Schafer, 1971; Cuypers *et al.*, 1975; Schneider, 1986). Mucous thread and clumps from the inner corner of the eye can be used to estimate particle deposition in the eyes (Schneider & Stockholm, 1981).

In the USA, the recommended standard procedure is to collect samples for fibre counting on a 0.8-μm pore size and 25- or 37-μm diameter Millipore type AA filter mounted in an open-face cassette (National Institute for Occupational Safety and Health, 1977b, 1980, 1984). The same procedure is required by the US Occupational Safety and Health Administration (1986) in its enforcement of the asbestos standard. The sampler is mounted either in a worker's breathing zone or on individuals in both occupational and nonoccupational environments whose exposure is to be characterized. Air is drawn through the filter with a battery-powered personal sampler pump at a rate of 2 l/min for 30 min. Fibres are then counted and sized by area fields defined by a calibrated graticule using phase-contrast microscopy at 400–450× magnification. The number of fields counted (100) and the uncertainty in fibre count as a function of total fibre count are specified. Results have been reported as total fibres/cm^3 air and as fibres in selected diameter and length classification, with fibres >5 μm in length and <3 μm in diameter as the predominant reporting mode. The latter corresponds to the definition of fibre size in compliance with the Federal work place standard for asbestos. Total or respirable dust concentrations are typically determined with a 37-mm membrane filter at a sampling rate of 2 l/min. The filter and sample are desiccated and reweighed, and the airborne particulate, expressed as mg/m^3, is calculated for the sampling rate and the filter weight gain (National Institute for Occupational Safety and Health, 1984).

In the method of the World Health Organization (1985), using optical microscopy, the filter is rendered optically transparent, and the fibres present within randomly selected areas are counted using a phase-contrast microscope with a magnification of 500×. The total number of fibres on the filter is calculated to give the airborne concentration. The microscopic techniques are based on those commonly adopted for asbestos monitoring. A fibre is defined as any particle that has a length >5 μm and a length:diameter ratio >3; a respirable fibre is any such fibre with a diameter <3 μm. 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 specified. The performance of the microscopic counting system is tested by using a standard test slide. Criteria have been established to count fibres that are branching or crossing or that are attached to other particles, and the correct criteria must also be used for counting fibres that are not completely within the counting field (World Health Organization, 1985). Some rules may overestimate the prevalence of long fibres. For example, if all fibres located wholly or partly in a field of view are sized, fibre length will be overestimated, and, since length is correlated to diameter, the diameter distribution will also be distorted (Schneider, 1979b).

The diameter distribution of bulk materials is often expressed as accumulated length within each given diameter interval (accumulated lengths or length-weighted diameters), because this distribution is independent of the method of sample preparation. The median is called the nominal diameter of the material. Diameter distributions generated in terms of number frequency *versus* fibre diameter are also used. This procedure results in a smaller nominal diameter (Schneider & Holst, 1983).

In optical microscopy, the limit of visibility is about 0.2 μm. For conventional man-made mineral fibres, this is no great disadvantage, since only a small percentage of fibres with lengths >5 μm are thinner. The median diameter of airborne fibres such as microfibres and other special-purpose fibres, however, can range from 0.1 to 0.3 μm, and therefore a substantial proportion of these 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 (UK Factories Inspectorate, 1987). With the method of the World Health Organization (1985), a detection limit of 0.05 fibre/cm^3 can normally be achieved without difficulty, and lower detection levels may be possible under circumstances in which contamination from other particles is negligible. The risk of obtaining false-positive results can be reduced by adding polarization analysis to phase-contrast microscopy: with this method, detection limits of <0.001 fibre/cm^3 can be obtained (Schneider, 1986).

Scanning electron microscopy is the method of choice for accurate identification of fibre type and for accurate sizing; with a magnification of 5000×, it is possible to detect fibres of about 0.05 μm in diameter. To ensure consistent results, instrument parameters must be specified. A reference method for measuring the size distribution of airborne man-made mineral fibres in work place air, including rules for evaluating fibres that are branching, crossing or attached to other particles, has been published (World Health Organization, 1985). Samples for scanning electron microscopy are taken on filters that have a smooth surface suitable for direct examination (Nuclepore). After sampling, part of the filter is cut

out, mounted on a specimen stub and coated, preferably with a thin layer of gold. In practice, the detection limit of scanning electron microscopy is about 0.1 μm (Middleton, 1982).

Transmission electron microscopy may be required to detect very thin fibres (Rood & Streeter, 1985). The elemental composition of individual fibres can be determined with an energy-dispersive X-ray analysis attachment combined with an electron microscope (Middleton, 1982). Fibres are counted and sized either on photomicrographs (World Health Organization, 1985) or directly on the screen.