94

SYNTHETIC VITREOUS FIBERS

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Target organ(s): Skin, eye, respiratory

Occupational exposure limits:

OSHA:

Regulated in *General Industry* as inert or nuisance dust:

Respirable fraction: 5 mg/m^3

Total dust: 15 mg/m^3

Shipyard: Fibrous glass

Respirable fraction: 5 mg/m^3

Total dust: 15 mg/m^3

Shipyard: Mineral wool

Respirable dust: 5 mg/m^3

Total dust: 15 mg/m^3

NIOSH: Fibrous glass dust:

Total dust: 5 mg/m^3

Fibers with diameter equal or <3.5 μm, and length ≥10 μm: 3 f/cc

RCF: REP 0.5 f/cc with action level of 0.25 f/cc

ACGIH: Synthetic vitreous fibers

Continuous filament glass fibers: 1 f/cc* A4

Continuous filament glass fibers: 5/mg/m^3** A4

Glass wool fibers: 1 f/cc* A3

Rock wool fibers: 1 f/cc* A3

Slag wool fibers: 1 f/cc* A3

Special purpose glass fibers: 1 f/cc* A3

Refractory ceramic fibers: 0.2 f/cc* A2

MRLs: A minimal risk level (MRL) of 0.03 WHO fibers/cc has been derived for chronic-duration inhalation exposure to refractory ceramic fibers

Risk/safety phrases: [list information for classification and labeling]

Post warning labels and signs (in English and the predominant language of workers who do not read English, or verbal) describing the health risks associated with RCF at entrances to work areas and inside work areas where airborne concentrations of RCF may exceed the REL

Depending on work practices and the airborne concentrations of RCF's state on the signs the need to wear protective clothing and the appropriate respiratory protection for RCF exposures above the REL

BACKGROUND AND USES

Man-made mineral fibers as the name suggests do not occur in nature. It is a generic name for a group of silica-based inorganic fibers manufactured from varying concentrations of rock, slag, glass, clay, and processed inorganic oxides. Other names include man-made vitreous fibers (MMVF), vitreous fibers,

*Fibers longer than 5 μm; diameter <3 μm; aspect ratio >5 : 1 as determined by the membrane filter method at 400–450× magnification (4-mm objective) phase contrast illumination.

**Measured as inhalable particle

A2: Suspected human carcinogen

A3: Confirmed animal carcinogen

A4: Not classifiable as a human carcinogen

Hamilton & Hardy's Industrial Toxicology, Sixth Edition. Edited by Raymond D. Harbison, Marie M. Bourgeois, and Giffe T. Johnson.

manufactured vitreous fibers, synthetic vitreous fibers, glass wool (GW), continuous glass filament, special purpose glass fiber, or mineral wool. Depending on the process, MMVF are produced as a mass of tangled, discontinuous fibers of varying length and diameters or as filaments, which are continuous fibers of intermediate length with diameters that are more uniform and typically thicker than wool (IARC, 2002). Their noncrystalline or amorphous molecular structure facilitates early removal from the lung parenchyma, which differentiates them from crystalline forms of fibers.

In an effort to reflect the changes in industry as well as consider the variability in toxicity and the potential for causing cancer among the groups of MMVF, the World Health Organization (WHO) updated and expanded the classification of man-made mineral fibers into two main categories: filaments that include continuous glass filament and wools that include glass (insulation and special purpose), rock (stone), slag, refractory ceramic fibers (RCF), and other unspecified fibers, including high temperature (HT), high alumina, low silica, or alkaline earth silicate (AES) wools. The term whisker is used for thin inorganic fibers in crystalline form, which are placed in a different category. Examples include potassium titanate, potassium octatitanate, and silicon carbide, which unlike amorphous inorganic forms of MMVF have definite fibrogenic potential in lung tissue. In addition to the inorganic form, man-made fibers also occur in the organic form. These include natural polymers, most commonly viscose made from cellulose, or synthetic polymers, which include acrylic, polyester, polyurethane, and nylon (Figure 94.1).

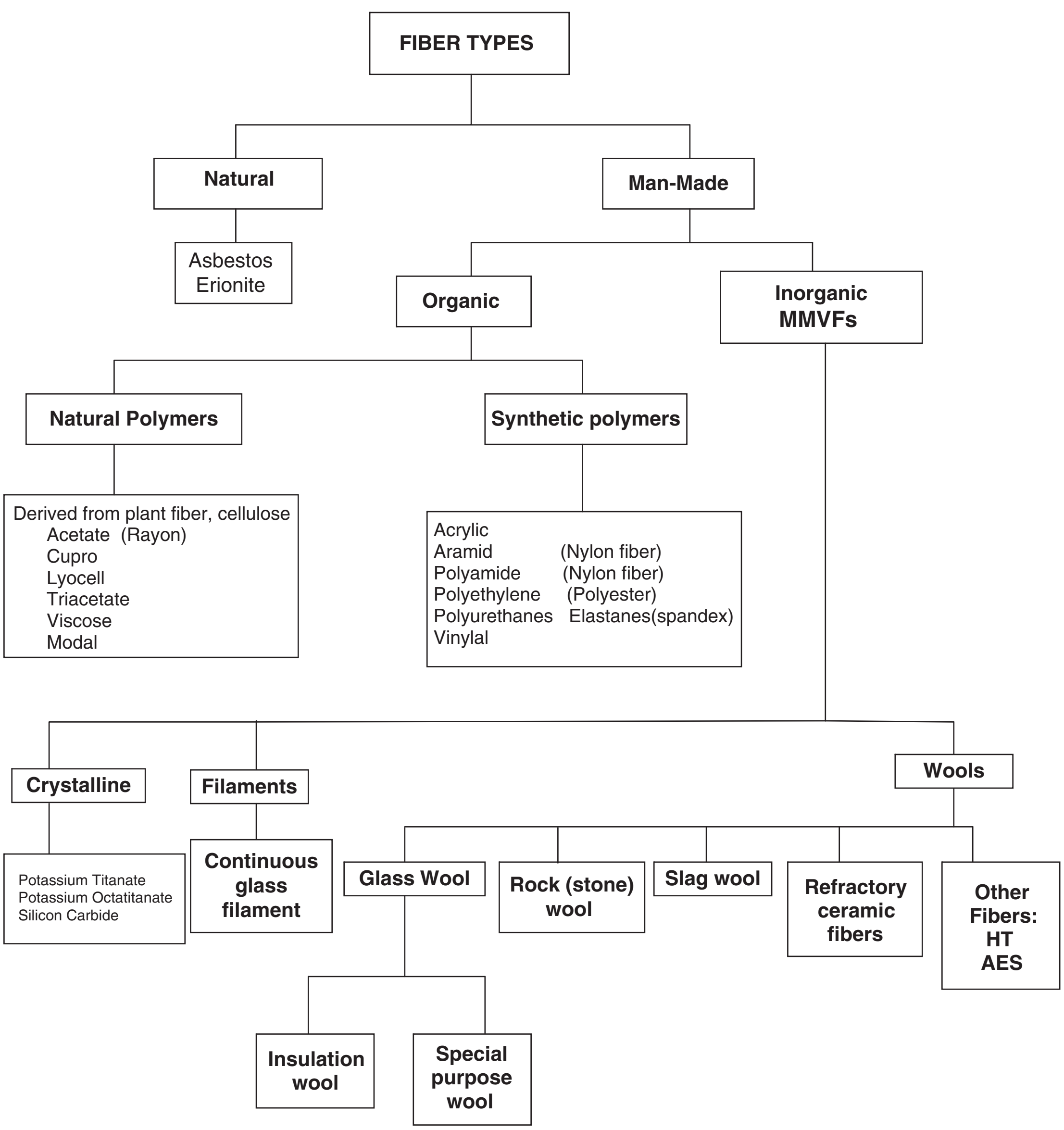

FIGURE 94.1 Classification of man-made fibers.

Historically, organic fibers have not been associated with occupational lung disorders until recently when a cluster of unexplained interstitial lung disease cases developed in the nylon flocking industry (Kern et al., 1998). In 2002, the WHO estimated that over 9 million tons of MMVF were produced annually in over 100 factories around the world. Primary applications include thermal or acoustical insulation where GW (~3 million tons, used predominately in the North America), and rock (stone) and slag wools (~3 million tons, used predominately in Europe and the rest of the world) are used in many cases as a replacement for asbestos. More recently, rock (stone) and slag wools have been replaced by high alumina, low silica wools (~1 million tons) for these applications. Special purpose glass developed for its durability is used in applications that require thermal insulation, such as the aircraft industry as well as for other purposes, including filtration media and batteries. Continuous glass fibers (~2 million tons) are used as reinforcement of plastics and textiles in the automobile, electrical, and building industries. Refractory ceramic fibers (150 thousand tons) are most often used during HT applications as insulation for furnaces and heaters (IARC, 2002). Alkaline earth silicate wools (~20,000 tons), developed in the 1980s in response over the fibrogenic and malignant potential of RCF, are a new class of fibers capable of being used as a substitute in a wide range of HT applications (Brown et al., 2012).

PHYSICAL AND CHEMICAL PROPERTIES

Man-made mineral fibers are divided based on the method of production, chemical composition, and application. Glass fibers, which include continuous filament fibers and GW, consist mainly of silicon dioxide and varying amounts of intermediate stabilizers, including aluminum, zinc, and titanium. Other oxides acting as modifiers include lithium, potassium, calcium, magnesium derived from dolomite, or boric acid from calcium borate. Varying the concentration of stabilizers and modifiers will alter the chemical and physical properties of the fiber resulting in changes in durability, heat and water resistance, and in solubility. The average diameter of continuous glass fibers ranges from 3 to 25 µm with lengths solely dependent on the industrial process. Ordinary GW diameters range from 3 to 15 µm and special purpose GW have diameters ranging from 0.1 to 10 µm. Category "c" fibers are considered special application fibers and make up <1% of the total glass fibers produced. The ability to distinguish between several types of glass fibers depends not only on the dimensions but also on their composition (Table 94.1).

Mineral wool is a term used to describe rock (stone) and slag wools in the United States, although in Europe, GW is included in the category. Rock and slag wools are composed mainly of calcium, aluminum, or magnesium silicates (-Table 94.2). Rock wool (RW) is derived by heating igneous rocks (basaltic, diabase, or olivine), which are classified based upon their alkali–silica content. Slag wool is produced by melting and fiberizing slag (wastes) from furnace iron and other raw materials, including clay, sand, and limestone. Naturally, the chemical properties will be dependent on the content of the slag that is used. Bonded wool is produced with the addition of urea–phenolic resin and is processed into ceiling tiles or used for blown insulation or other insulation material. The manufacturing process using centrifugation produces discontinuous fibers with diameters ranging from 3.5 to 7 µm.

TABLE 94.1 Composition of Various Glass Fibers

	Type of Glass Fiber, % by Weight				
Component	C	D	E	S	AR
SiO_2	55–65	72–75	52–56	55–85	60–70
AL_2O_3	1–5	0	12–16	10–35	0–5
Fe_2O_3	0.1–0.3	0	0–0.5	0–0.5	0.1
CaO	7–14	0	16–25	0	0–10
MgO	2–4	0	0–6	4–25	0
B_2O_3	6–9	0–23	7–13	0	0
ZrO_2	0	0	0	0	15–22
Na_2O	8–16	0–4	0	0	10–15
K_2O	0.4–0.7	0–4	0–0.2	0	0–2
TiO_2	0.02	0	0	0	0–5

Source: Compiled from ATSDR (2004), Lee et al. (1981), Naval Environmental Health Center (1997).

C fibers (chemical glass) typically glass wool and resistant to acids.

D fibers are sold a textile yarns.

E fibers (electrical glass) resistant to water and used for electrical applications.

S glass has the highest tensile strength and stiffness.

AR glass (alkali resistant) used for strengthening cement.

TABLE 94.2 Fiber Composition by Percent Weight of Mineral Wool and Ceramic Fibers

Component	Rock Wool	Slag Wool	Kaolin	Zirconia	Aluminum Silicate and Al Silicate	High Purity AES Wool	High Alumina Low Silica
SiO_2	37–53	32–52	49–53	5–50	95–97	50–82	33–42
AL_2O_3	6–14	5–15	43–50	5–95	95–97	<2	18–24
Fe_2O_3	0.5–11.6	0–8.2	0.06–2	<0.05	0.5–1		
CaO	10–30	10–43	<0.1	<0.05	<0.05	18–43	23–33
MgO	6–16	4–15	<0.1	0.01	0.01		
B_2O_3	0	0	0	0	0	<1	
ZrO_2	0	0	0.1	15–92	0	0–6	
Na_2O	1–3.5	0.8–3.3	0–0.5	<0.3	0.1–0.2	<1	1–10
K_2O	0.5–2	0.3–2	0.03–2	<0.01	0		
TiO_2	0.5–3.5	0.4–2.7	0.02–1	0.04	0.7–1.3		0.5–3
FeO	3–12	0–2	0	<0.05	0		3–9

Source: Compiled from ATSDR (2004), Lee et al. (1981), Naval Environmental Health Center (1997), Brown et al. (2012).

Refractory ceramic fibers sometimes called refractory fibers or ceramic fibers are characterized by their ability to withstand temperatures as high as 3000 °F and are used primarily for HT or aerospace applications. Refractory fibers consist mainly of kaolin clay, aluminum silicate with various metallic oxides (chromous, zirconia), or highly purified aluminum silicate (Table 94.2). Where HT applications are needed, fibers can contain more the 90% zirconia oxide. Ceramic fibers are unique in that they occur initially as amorphous structures but when heated the alumina–silica matrix changes to mullite, forming an aluminosilicate crystalline compound (Naval Environmental Health Center, 1997; IARC, 2002). As temperatures approach 1100 °C, excess silica is crystallized in a process known as devitrification to form crystabalite, which is considered to be carcinogenic to humans. Fibers containing higher concentrations of aluminum or zirconium oxides are able to retain their chemical structure and physical characteristics even when exposed to HTs. The average diameter of RCF ranges from 1 to 5 µm (Naval Environmental Health Center, 1997; WHO, 2000).

Alkaline earth silicate wools are produced by melting a combination of silica, calcium and magnesium oxide, alumina, titania, zirconis, and trace oxides. Commercially available in the 1990s they are primarily used in industrial equipment, fire protection, and automobile exhaust systems.

Manufacturing Process

The production of MMVF first involves liquefying raw materials, including sand, kaolin, aluminum silicate, or igneous rock, where they can be solidified and used at a later date or they can be used immediately. Continuous fibers or filaments are produced exclusively from glass, as the molten material is extruded using a set of bushings or spinerettes. Insulation wools are constructed as molten raw materials are extruded through small holes in a rotary or centrifugal method, producing fibers of variable diameters. When the molten glass emerges from the holes, they are stretched by a rotary or centrifical force and cooled by air into individual fibers. The diameters of these fibers can be adjusted with great accuracy and reproducibility to 6–25 µm. Flame attenuation refers to the special purpose glass fibers that are remelted by a jet flame blast after they are stretched into individual fibers. They are typically used for extreme temperature applications such as the skin of the space shuttle.

Once the fiber is made, various binding resins, including phenol formaldehyde, are used to give structure and rigidity to the fiber. Because glass filaments are fragile, sizings are added and used as a protective coating to increase the adhesion between the fibers. These include polyvinyl silane, epoxy silane, and polyvinyl acetate chrome chloride mixtures. Other lubricating or paraffin oils can be added to decrease dust generation during production of the end product (Naval Environmental Health Center, 1997; ATSDR, 2004).

MAMMALIAN TOXICOLOGY

Acute Effects

Skin irritation is the most common health effect associated with an exposure to MMVF. Irritation is usually related to mechanical trauma from coarse fibers measuring 4–6 µm in diameter. Irritation is reduced or resolves completely with continued exposure but returns when there is a lapse or interruption in an exposure for a few days (Lockey and Ross, 1998; Stam-Westerveld et al., 1994). Less commonly, allergic contact dermatitis resulting from sensitization to epoxy resins or hardening by-products used for finishing glass fibers or reinforced plastics have been described (Minamoto et al., 2002; Nogueira et al., 2011; Jolanki et al., 1990).

Symptoms of dry cough, eye, nose, and throat irritation have also been described (Burge et al., 1995) and appear associated with dusty working conditions >1 f/cc involving removal of fiberglass materials in closed spaces without respiratory protection (ATSDR, 2004).

Chronic Effects

Reports of airflow obstruction (Hansen et al., 1999), decrements in forced expiratory volume (FEV_1) (Trethowan et al., 1995; Clausen et al., 1993) irregular opacities, and pleural plaques (Lockey et al., 2002) have been described in workers exposed to MMVF; however, no consistent evidence for increased prevalence of any of these exists.

The National Institute for Occupational Safety and Health (NIOSH) (NIOSH, 2006) concluded that an exposure to RCF may pose a carcinogenic risk based on the results of chronic animal inhalation studies. Likewise, the National Toxicology Program (NTP) concluded that inhalable glass fibers and ceramic fibers of respirable size (3 μm in diameter and length to width (aspect) ratio of 3 : 1) were reasonably anticipated to be human carcinogens based on animal studies (National Toxicology Program). Despite this, epidemiologic studies of workers exposed to MMVF have failed to reveal an increased risk of respiratory cancer or mesotheliomas. In 2009, Lipworth conducted a systemic review and meta-analysis of risk estimates of lung and head and neck (HN) cancer in epidemiologic studies of workers exposed to MMVF, specifically RW and GW and concluded:

> despite a small elevation in RR of lung cancer among MMVF production workers, the lack of excess risk among end users, the absence of any dose-risk relation, the likelihood of detection bias, and the potential for residual confounding by smoking and asbestos exposure argue against a carcinogenic effect of MMVF, RW or GW at this time. Similar conclusions apply to HN cancer risk among workers exposed to MMVF
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> (Lipworth et al., 2009).

Marsh performed a systemic review of the literature published following the 2001 International Agency for Cancer Research (IARC) decision to downgrade insulation GW from a Group 2B to Group 3 carcinogen. Utilizing selected Bradford Hill criteria for the evaluation of epidemiologic associations, they found no statistical significant increase in the incidence of respiratory cancer in workers exposed to MMVF (Marsh et al., 2011). Similarly, as others have mentioned (SCOEL/SUM/88 March, 2012), the NTP concludes,

> the data available from studies in humans inadequate to evaluate the relationship between human cancer and exposure to glass wool fibers. Although studies of occupational exposure found excess lung-cancer mortality or incidence, it is unclear that the excess lung cancer was due to exposure specifically to glass wool fibers, because (1) no clear positive exposure-response relationships were observed (however, misclassification of exposure is a concern), and (2) the magnitudes of the risk estimates were small enough to potentially be explained by co-exposure to tobacco smoking.

The investigators further conclude that the data available from epidemiological studies are inadequate to evaluate the relationship between human cancer and exposure specifically to respirable ceramic fibers (National Toxicology Program).

Mechanism of Action(s)

Fiber toxicity is related to three essential factors that are as follows: An exposure to a sufficient *dose* of respirable fibers with the correct aerodynamic *dimensions* to allow deposition in the terminal portions of the lung (alveoli) and finally, after inhalation, *durability* of a fiber that will allow it to persist in the lung for long periods of time. In addition to the 3 Ds (dose, dimension, durability), alveolar macrophages, surface properties, the chemical composition and biopersistence of the fibers play a role in the elimination and half-life of the fiber.

Respirable fibers or dusts are defined by their ability to bypass the protection mechanisms of the upper airway and lodge on the alveolar surfaces of the lung. Lung deposition depends on the aerodynamic diameter of the fiber. Inhalable fibers, considered fibers with diameters of 3 μm or less with an aspect ratio (length/diameter ratio) >3, will be deposited in the lower airway. Fibers present particular problems because they can be of lengths >15–20 μm yet align parallel to the air current and be inhaled into the lower airway. Fiber dose is dependent on the length since long fibers are unable to be completely engulfed by the alveolar machrophages and thus cleared from the lung. Unlike asbestos fibers that tend to arrange in bundles and are split longitudinally, MMVF tend to occur as individual fibers and break transversely into shorter segments, which allows easier and earlier removal.

Once a fiber enters the lower respiratory tract, clearance is enhanced through removal by mucociliary transport or by the alveolar macrophage. Only those fibers <10 μm can be effectively phagocytized by alveolar machrophages (Oberdörster, 1997; Tran et al., 1996; SCOEL/SUM/88 March, 2012). Incomplete phagocytosis occurs with fibers >20 μm, which in turn leads to an inflammatory and fibrotic response that is associated with activation of various cell lines, including neutrophils, lymphocytes, mast cells, and fibroblasts. This stimulates the release of inflammatory mediators and chemokines (tumor necrosis factor α (TNFα), interleukin-1α, interleukin 6 and 8, basic fibroblast growth factor, MIP-1α, growth regulated peptide) and generates reactive oxygen and nitrogen species leading to epithelial and mesothelial cell proliferation (Ishihara, 2001; Churg et al., 2000; Driscoll, 1996; ATSDR, 2004; Morimoto et al., 1999).

Reactive oxygen species (ROS)have also been shown to induce cell injury and death by lipid peroxidation through interaction with fatty acids in the cell membrane. Alveolar macrophages isolated by bronchoalveolar lavage (BAL) and exposed to mineral and chrysotile fibers increase the production of superoxide anion and hydrogen peroxide, depleting the level of glutathione and increasing serum Ca in alveolar macrophages (Wang et al., 1999). Under more acidic conditions, the release of iron from MMVF, particularly refractory fibers, results in the production of hydroxyl free radicals in a similar way as amphibole asbestos (Brown et al., 1998). Further, the release of ROS through contact with highly durable fibers may activate signaling pathways and trigger the secretion of additional growth factors, proteases, and other proinflammatory cytokines (Nguea et al., 2008). Still other mechanisms of MMVF-induced cytotoxicity may involve the depletion of adenosine triphosphate (ATP) in the alveolar macrophage resulting in cell death (Kim et al., 2001). And finally, translocation of fibers from the lung parenchyma to the pleura may play a role in fiber-induced pleural disease (Gelzleichter et al., 1996).

The mechanism of fiber-induced genotxocity has been investigated using various types of MMVF that have been shown to produce 8-OHdG (possibly resulting in miscoding during DNA replication) (Jaurand, 1997), induce the occurrence of micronuclei and/or polynuclei abnormalities (Hart et al., 1992), stimulate morphologic transformation (Gao et al., 1995) and squamous metaplasia (preneoplastic characteristics) (Woodworth et al., 1983). Long fibers appear to induce the production of bi/trinucleated cells (an early event in asbestos-induced cancers) through incomplete or failed cytokinesis (Jenson and Watson, 1999) and result in oxidative DNA damage, all of which are considered precursors to the initiation of the cancerogenic process (Cavallo et al., 2004).

Chemical Pathology

As discussed, the dose and dimension play a key role in a fiber's ability to produce toxic effects in the lung. Fiber durability, the ability of a fiber to remain in the lung, is dependent on the dissolution rate (solubility) of the fiber. *In vitro* estimates of dissolution rate constants at varying pH for numerous fibers have been published and summarized by Maxim et al., 2006. The chemical components of the fiber influence the rate at which they dissolve. Man-made vitreous fibers composed of calcium, magnesium, and sodium tend to have faster dissolution rates, while alumina and silica tend to decrease the rate of dissolution making them less bio-soluble, thus allowing them to persist in the lung for longer periods of time. *In vitro* evidence suggests that slag wool and RCF dissolve more rapidly at a pH of 4 (simulating the environment following phagocytosis by the macrophage) as opposed to GW, which appears to dissolve more rapidly at a pH of 7.6 (simulating the extracellular environment). Thus the dissolution of fibers may involve both the intra- and extracellular environment and is accompanied by varying degrees of compositional and physical changes to the fiber. Changes in fiber morphology or dimension may in turn alter both the physical and surface chemical properties, ultimately affecting their overall biological reactivity (Bauer et al., 1994). Much of the current research regarding newer formulations of man-made mineral fibers has centered on the development of products that break down easier and faster yet retain their industrial functions. Newer fibers tend to have higher solubility, in essence, limiting the biopersistence and health effects. Biopersistence is therefore the duration a fiber remains in the lung and is determined by the physiologic/mechanical clearance as well as the chemical properties and dissolution rate of the fiber.

SOURCES OF EXPOSURE

Occupational

The IARC concluded that the worldwide average exposure levels during production, processing, and use of these fibers is thought to be generally <0.5 respirable fiber/cm^3 as an 8-h time-weighted average (TWA) (IARC, 2002). Those involved in the manufacture, installation, service, removal/repair, or use of these products are expected to be exposed to higher concentrations of the fibers.

Recently in the United States, the Health and Safety Partnership Program (HSPP), a workplace safety program for workers involved in the application of glass and mineral wool products and developed to create an occupational exposure database in the synthetic fiber industry, reported mean concentrations of 0.23–0.28 f/cc for the GW industrial sector and a mean of 0.38 f/cc for those involved in GW installation. Analysis of the mineral wool sector revealed a mean of 0.19 f/cc, with the highest levels in the manufacturing sector with a mean of 0.20 f/cc. In general, airborne concentrations of fibers measured during the production of glass and mineral wool (slag, and/or rock (stone)) are below 1 f/cc, except in areas where small diameter fibers (<1 μm) are produced (aircraft insulation, separation and filtration media) or specific products are used (blowing wool with binder) (Marchant et al., 2002).

Recently, an update to ongoing monitoring studies of an occupational exposure to RCF at plants that produce RCF and customer facilities in the United States was reported by Maxim et al. (2008), who found workers at RCF manufacturing plants to be exposed to TWA concentrations of ≤0.5 f/cc 95.8% of the time and when corrected for respirator use, 97.8% were at or below that level. The average TWA concentration of ceramic fibers adjusted for respiratory use from 2002 to 2006 was 0.28 f/cm^3 (NTP, 2011).

Environmental

Exposures to airborne MMVF in both occupational and environmental settings primarily occur as the result of construction, installation, maintenance/repair, physical damage, by degradation, or as MMVF are released to the environment over time. Much of the literature reporting on airborne levels of MMVF in commercial, residential, or ambient air fails to distinguish between organic (cellulose, cotton, nylon), inorganic mineral fibers (silicates and sulfates), or MMVF. Despite these limitations, it appears that an exposure to MMVF in indoor or environmental air is 2–3 orders of magnitude less than the exposure that occurs in an occupational environment (IARC, 2002). Mean air concentrations in 79 buildings containing MMVF products (Gaudichet et al., 1989) ranged from none detectable to 0.006 f/cm^3, in 16 schools none detectable to 0.08 f/cm^3 (Schneider, 1986), and more than 130 measurements of indoor air in various locations (office buildings, schools, laboratories, private homes) was none detectable to 0.038 f/cm^3 (IARC). In the 1990s, Carter et al. (1999) sampled residential and commercial buildings while taking 21 simultaneous samples from 19 locations using scanning electron microscopy (SEM) to distinguish among the fiber types. The indoor respirable fiber levels averaged 0.008 f/cm with a maximum of 0.029 f/cc using phase contrast optical microscopy (PCOM). Ninety seven percent of the respirable fibers identified by SEM were determined to be organic. Inorganic fiber levels measured indoors using SEM averaged <0.0001 f/cc. The ambient air samples revealed a mean of 0.002 f/cc by PCOM.

INDUSTRIAL HYGIENE

The Occupational Safety and Health Administration (OSHA) estimates that there are more than 225,000 workers in the United States who are exposed to MMVF in manufacturing and end-use applications (OSHA, 2002). Mineral fibers are currently regulated only as a nuisance dust in general industry as OSHA has no specific permissible exposure limit (PEL) for an occupational exposure to fibrous glass. Inert or nuisance dust is regulated to 15 mg/m^3 for total dust and 5 mg/m^3 for respirable fractions. For employees involved in ship repairing, shipbuilding, shipbreaking or related employments, fibrous glass, and mineral wool (including rock or slag), the PEL is 15 mg/m^3 for total dust and 5 mg/m^3 for respirable fractions. In 1999, the OSHA partnered with various trade organizations and major manufacturers of fiberglass, slag and rock wool insulation products to institute a voluntary HSPP for fiberglass and mineral wool. The program established a voluntary PEL of 1 f/cc 8-h TWA for respirable synthetic mineral fibers (glass/rock/slag wool). The HSPP also established a database, monitored by the North American Insulation Manufacturers Association) (NAIMA), of representative exposure limits for workers involved in manufacturing and end-use applications. It was also recommended that workers wear NIOSH-certified dust respirators when the PEL is exceeded or when performing certain tasks such as blowing SVF insulation into attics and other places and when demolishing buildings.

The current guidelines from the American Conference of Governmental Industrial Hygienists (ACGIH) adopted a threshold limit value (TLV) for an 8-h TWA of 1 f/cc for continuous glass filaments with a A4 (not classifiable as a human carcinogen) rating and 1 f/cc for GW, rock and slag wools, and special purpose fibers with an A3 (confirmed animal carcinogen with unknown relevance to humans) rating. A TLV–TWA of 0.2 f/cc was adopted for RCF with an A2 (suspected human carcinogen) rating (ACGIH, 2001).

In 1977, the NIOSH established a recommended exposure limit of (REL) of 3 f/cc^3 as a TWA for glass fibers with diameters ≤3.5 μm and lengths ≥10 μm for up to 10 h/day during a 40-h workweek. The NIOSH also recommended that airborne concentrations determined as total fibrous glass be limited to a 5 mg/m^3 of air as a TWA. In an effort to minimize the risk of lung cancer and irritation of the eyes and upper respiratory tract, the NIOSH proposed a REL for RCF of 0.5 f/cm^3 of air as a TWA and an action level of 0.25 f/cm^3 (used for determining when additional actions should be taken to reduce RCF exposures) (NIOSH, 2006). They further recommended that all reasonable efforts be made to reduce exposures to <0.2 f/cm^3 where cancer risk estimates between 0.03/1000 and 0.47/1000 have been extrapolated from risk models (Moolgavkar et al., 1999; Maxim et al., 2003).

Exposure control and prevention is aimed at limiting exposure through a combination of engineering controls and workplace practices. Airborne concentrations can be reduced by adequate ventilation and local exhaust systems, tool selection, modifying workplace practices, and isolation of the manufacturing process to enclose airborne fibers and separate them from the workers. Personal protective equipment is geared at reducing skin, eye, and respiratory irritation and should include long sleeves, gloves, and eye protection when performing dusty activities involving MMVF. When airborne concentrations of RCF exceed the REL, the NIOSH recommends the following respiratory protection: At a minimum, use a half-mask, air-purifying respirator equipped with a 100 series particulate filter (this respirator has an assigned protection factor (APF) of 10. For a higher level of protection and for prevention of facial or eye irritation, use a full facepiece, air-purifying respirator (equipped with a 100 series filter) or any powered, air-purifying respirator equipped with a tight-fitting full facepiece. For greater respiratory protection when the work involves potentially high airborne fiber concentrations (such as removal of after-service RCF insulation such as furnace insulation), use a supplied-air respirator equipped with a full facepiece, since airborne exposure to RCFs can be high and unpredictable (NIOSH, 2006).

MEDICAL MANAGEMENT

For workers exposed to MMVF, a medical monitoring program should be established by providing a baseline medical examination within 3 months of employment. The exam should include a detailed occupational history that gathers information about past jobs, dust or fiber exposures and should include a physical exam with emphasis placed on the skin and respiratory tract, spirometry, chest X-ray, and other tests deemed necessary by the health-care provider. Suggested guidelines for the frequency of periodic examinations have been published by the NIOSH who recommend examinations every 5 years for workers exposed to RCF with fewer than 10 years since first exposure and for those with 10 years or more since first exposure, every 2 years. More frequent evaluations may be required depending on the dose, duration, and intensity of exposures, new or worsening respiratory symptoms, recurrent or chronic dermatitis, exposure to other respiratory hazards (i.e., asbestos), or changes in the job process. Programs should be monitored periodically to identify patterns where workplace practices are linked to worker health and well-being. In addition, medical monitoring programs may be useful in identifying changes needed in job processes or specific exposure conditions.

REFERENCES

ACGIH (2001) *Synthetic Vitreous Fibers. Supplement to Documentation of the Threshold Limit Values and Biological Exposure Indices*, Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

ATSDR (2004) *Toxicological Profile for Synthetic Vitreous Fibers*, Atlanta, GA: U.S. Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry.

Bauer, J.F., et al. (1994) Dual pH durability studies of man-made vitreous fiber (MMVF). *Environ. Health Perspect.* 102(Suppl. 5):61–65.

Brown, D.M., et al. (1998) Free radical activity of synthetic vitreous fibers: iron chelation inhibits hydroxyl radical generation by refractory ceramic fiber. *J. Toxicol. Environ. Health* 53:545–561.

Brown, R.C., et al. (2012) Alkaline earth silicate wools—a new generation of high temperature insulation. *Regul. Toxicol. Pharmacol.* 64:296–304.

Burge, P.S., et al. (1995) Are the respiratory health effects found in manufacturers of ceramic fibres due to the dust rather than the exposure of fibres. *Occup. Environ. Med.* 52:105–109.

Carter, C.M., et al. (1999) Indoor airborne fiber levels of MMVF in residential and commercial buildings. *Am. Ind. Hyg. Assoc. J.* 60:794–800.

Cavallo, D., et al. (2004) Cytotoxic and oxidative effects induced by man-made vitreous fibers (MMVFs) in a human mesothelial cell line. *Toxicology* 201:219–229.

Churg, A., et al. (2000) Pathogenesis of fibrosis produced by asbestos and man-made mineral fibers: what makes a fiber fibrogenic? *Inhal. Toxicol.* 12:15–26.

Clausen, J., Netterstrom, B., and Wolff, C. (1993) Lung function in insulation workers. *Br. J. Ind. Med.* 50:252–256.

Driscoll, K.E. (1996) Effects of fibres on cell proliferation, cell activation and gene expression. *IARC Sci. Publ.* 140:73–96.

Gao, H.G., et al. (1995) Morphological transformation induced by glass fibers in BALB/c-3T3 cells. *Teratog. Carcinog. Mutagen.* 15:63–71.

Gaudichet, A., et al. (1989) Levels of atmospheric pollution by man-made mineral fibres in buildings. In: Bignon, J., Peto, J., and Saracci, R., editors. *Non-Occupational Exposure to Mineral Fibres*, IARC Scientific Pub. No. 90. Lyon, France: IARC, pp. 291–298.

Gelzleichter, T.R., et al. (1996) Pulmonary and pleural responses in Fischer rats following short-term inhalation of a synthetic fiber. II. Pathobiologic responses. *Fundam. Appl. Toxicol.* 30:39–46.

Hansen, E.F., et al. (1999) Lung function and respiratory health of long-term fiber-exposed stonewool factory workers. *Am. J. Respir. Crit. Care Med.* 160:466–472.

Hart, G.A., et al. (1992) Cytotoxicity of refractory ceramic fibres to Chinese hamster ovary cells in culture. *Toxicol. In Vitro* 6:317–326.

IARC (2002) Man-made vitreous fibers. In: *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans*, vol. 81, Lyon, France: International Agency for Research on Cancer.

Ishihara, Y. (2001) *In vitro* studies on biological effects of fibrous minerals. *Ind. Health* 39:94–105.

Jaurand, M.C. (1997) Mechanisms of fiber-induced genotoxicity. *Environ. Health Perspect.* 105(S5):1073–1084.

Jenson, C.G. and Watson, M. (1999) Inhibition of cytokinesis by asbestos and synthetic fibers. *Cell Biol. Int.* 23:829–840.

Jolanki, R., et al. (1990) Occupational dematoses from epoxy resin compounds. *Contact Dermatitis* 23:172–183.

Kern, D.G., et al. (1998) Flock workers lung: chronic interstitial lung disease in the nylon flocking industry. *Ann. Intern. Med.* 129:261–272.

Kim, K.A., et al. (2001) Depletion of intracellular ATP in the AM after refractory ceramic fibers or rockwool exposure diminishes cell viability and induces cytotoxicity. Mechanism of refractory ceramic fiber- and rock wool-induced cytotoxicity in alveolar macrophages. *Int. Arch. Occup. Environ. Health* 74:9–15.

Lee, K.P., et al. (1981) Pulmonary response and transmigration of inorganic fibers by inhalation exposure. *Am. J. Pathol.* 102: 314–323.

Lipworth, F., et al. (2009) Occupational exposure to rock wool and glass wool and risk of cancers of the lung and the head and neck: systemic review and meta-analysis. *J. Occup. Environ. Med.* 51:1075–1087.

Lockey, J.E., et al. (2002) A longitudinal study of chest radiographic changes in workers in the refractory ceramic fiber industry. *Chest* 121:2044–2051.

Lockey, J.E. and Ross, C.S. (1998) Health effects of man-made fibres. In: Stellman, J.M., editor. *Encyclopaedia of Occupational*

Health and Safety, 4th ed., vol. 1, Geneva, Switzerland: International Labour Office, pp. 74–78.

Marchant, G.E., et al. (2002) A synthetic vitreous fiber (svr) occupational exposure database: implementing the SVF Health and Safety Partnership Program. *Appl. Occup. Environ. Hyg.* 17:276–285.

Marsh, G.M., et al. (2011) Fiberglass exposure and human respiratory system cancer risk: lack of evidence persists since 2001 IARC re-evaluation. *Regul. Toxicol. Pharmacol.* 60:84–92.

Maxim, L.D., et al. (2008) Workplace monitoring of occupational exposure to refractory ceramic fiber—a 17-year retrospective. *Inhal. Toxicol.* 20:289–309.

Maxim, L.D., et al. (2006) The role of fiber durability/biopersistence of silica-based synthetic vitreous fibers and their influence on toxicology. *Regul. Toxicol. Pharmacol.* 46:42–62.

Maxim, D.D., et al. (2003) Quantitative risk analyses for RCF: survey and synthesis. *Regul. Toxicol. Pharmacol.* 38:400–416.

Minamoto, K., et al. (2002) Occupational dermatoses among fiberglass reinforced plastics factory workers. *Contact Dermatitis* 46:339–347.

Moolgavkar, S.H., et al. (1999) Quantitative assessment of the risk of lung cancer associated with occupational exposure to refractory ceramic fibers. *Risk Anal*. 19:599–611.

Morimoto, Y., et al. (1999) Effects of mineral fibers on the gene expression of proinflammatory cytokines and inducible nitric-oxide synthase in alveolar macrophages. *Ind. Health* 37:329–334.

National Toxicology Program, Department of Health and Human Services (2011) *Report on Carcinogens*, 12th ed., Research Triangle Park, NC: National Toxicology Program, Department of Health and Human Services.

Naval Environmental Health Center (1997) *Man-Made Vitreous Fibers. Technical Manual NEHC-TM6290.91 Rev. A*.

Nguea, H.D., et al. (2008) Macorphage culture as a suitable paradigm for evaluation of synthetic vitreous fibers. *Crit. Rev. Toxicol.* 38:675–695.

NIOSH (2006) *NIOSH (DHHS) Publication No. 2006-123; Occupational Exposure to Refractory Ceramic Fibers*.

Nogueira, A., et al. (2011) Systemic allergic contact dermatitis to fiberglass in a factory worker of wind turbine blades. *Cutan. Ocul. Toxicol.* 30:228–230.

Oberdörster, G. (1997) Pulmonary carcinogenicity of inhaled particles and the maximum tolerated dose. *Environ. Health Perspect.* 105(Suppl. 5):1347–1356.

Occupational Safety & Health Administration (OSHA) (2002) *Synthetic Mineral Fibers*. Available at https://www.osha.gov/SLTC/syntheticmineralfibers/.

Schneider, T. (1986) Manmade mineral fibers and other fibers in the air and in settled dust. *Environ. Int.* 12:61–65.

SCOEL/SUM/88 March 2012: Recommendation from the Scientific Committee on Occupational Exposure Limits for man made-mineral fibers (MMMF) with no indication for carcinogencicity and not specified elsewhere.

Stam-Westerveld, E.B., et al. (1994) Rubbing test responses of the skin to man-made mineral fibres of different diameters. *Contact Dermatitis* 31:1–4.

Tran, C.L., et al. (1996) Evidence of overload, dissolution and breakage of MMVF10 fibres in the RCC chronic inhalation study. *Exp. Toxicol. Pathol.* 48:500–504.

Trethowan, M., et al. (1995) Study of the respiratory health of workers in seven European plants that manufacture ceramic fibers. *Occup. Environ. Med.* 52:97–104.

Wang, Q., et al. (1999) Biological effects of man-made mineral fibers (i): reactive oxygen species production and calcium homeostasis in alveolar macrophages. *Ind. Health* 37:62–67.

WHO (2002) Chapter 8.2: Man-made fibers. In: *Air Quality Guidelines*, 2nd ed., Copenhagen, Denmark: WHO Regional Office for Europe. Available at http://www.euro.who.int/__data/assets/pdf_file/0004/123088/AQG2ndEd_8_2MMVF.pdf.

Woodworth, C.D., et al. (1983) Induction of squemous metaplasia in organ cultures of hamster trachea by naturally occurring and synthetic fibers. *Cancer Res*. 43:4906–4911.