#2457

Building and Environment, Vol. 21, No. 3/4, pp. 129–133, 1986
Printed in Great Britain.

0360–1323/86 $3.00+0.00
Pergamon Journals Ltd.

2457

AIVC
1945

Man-made Mineral Fibres in the Indoor, Non-industrial Environment

THOMAS SCHNEIDER*
GUNNAR R. LUNDQVIST†

Dust elimination and dust accumulation problems related to entrainment of man-made mineral fibres (MMMF) in spaces from continuous sources, such as interior materials or mechanical ventilation systems, are discussed. Ventilation rates lower than 4 ACH have virtually no effect on fibres larger than 10 μm which have maximum potential for causing skin, eye and possibly upper airway irritation. These fibres are removed almost exclusively by sedimentation. They are then available for skin contact, transfer via the fingers to the face and eyes or local redispersion unless they are constantly and efficiently removed by cleaning. Even the load from a weak source may be of importance if accumulation is allowed to occur. The settled fibres may then be the cause of complaints about the indoor environment and quantification of MMMF on surfaces should always supplement determination of airborne fibres.

INTRODUCTION

IT IS currently the subject of much concern among employees in day-care institutions, schools and office buildings in Denmark whether exposure to man-made mineral fibres (MMMF) in the indoor environment could cause discomfort or chronic health hazards even at low levels compared to threshold limit values for occupational exposure in industry and on construction sites.

The bulk of MMMF material used for insulation consists of fibres with a broad diameter distribution and with median diameters in the range 3–6 μm. Several methods of fiberizing break the molten mineral up into small droplets and as these droplets are swept out at high velocity, fibres are formed out of 'tails' from the head of the droplet. Non-fiberized droplets appearing in the mineral wool often have part of the tail sticking out as spicules and are referred to as 'shots'. Their size can be from several microns to several millimetres.

The sources of MMMF in the non-industrial, but occupational, environments are related to interior material surfaces containing MMMF, such as acoustic ceiling boards, wall coverings and floor materials as well as thermal insulation. Mechanical ventilation systems with friable mineral wool used in silencers and air ducts could be a source too.

It has also been shown that MMMF from the thermal insulation in one-storey buildings are able to penetrate the vapour barrier [1].

Smarting eyes, watering eyes, swollen eyelids, disturbance of sight, increase in conjunctival hyperaemia and smarting in the nose have been reported as acute symptoms of exposure to MMMF in indoor spaces with ceiling boards of compressed mineral wool [2].

However, these reports were not followed up by assessment of the exposure level as measured in fibres per cubic metre (f m^{-3}) or specification of fibre size distribution. It is known, that MMMF sources can build up concentrations of airborne MMMF of the order of 100–100,000 f m^{-3}, but in most cases less than 10.000 f m^{-3} at the upper confidence limit value [1, 3]. This is less than 1/100 of the tentative Danish TLV for occupational exposure which is 10^6 f m^{-3} (respirable, i.e. diameter ≤ 3 μm) for a workday exposure in factories or on construction sites. The median diameter is usually of the order of 1 μm.

It has also been shown [1, 3] that MMMF can accumulate in considerable numbers on surfaces which are overlooked in the routine cleaning procedure. The median diameter of these settled fibres was 3–4 μm. Approximately 5% had diameters exceeding 10 μm. The skin-irritation potential is virtually non-existent for fibre diameters less than 5 μm and increases to maximum potential for diameters exceeding 10 μm [4].

The potential of exposure to the low airborne MMMF levels to cause discomfort to occupants, and especially the role of the airborne fibre concentration as compared to settled fibres, has been discussed [3]. It was concluded that settled fibres may be more important than airborne fibres in causing skin and eye irritation. Fibre transfer could, for example, be by direct transfer to the skin or by transfer via fingers to the face and eyes, in a similar way as previously described for industrial settings [5]. It has been reported that irritation from body contact with

* National Institute of Occupational Health, Hellerup, Denmark.
† Institute of Hygiene, University of Aarhus, Denmark.

BAE 21:3/4-A

clothing or other articles such as bed sheets, which have been washed with fibrous glass textiles, or in a container previously used for washing without thorough cleaning, may result in irritation [5]. One can therefore expect that for example, children playing on pillows, mattresses, etc. in kindergartens also experience skin irritation from settled fibres. Proper showering is not able to completely remove MMMF from the skin of workers [6]. Thus, once MMMF have contaminated textiles such as carpets, cushions and mattresses or even clothes, they may be hard to get rid of.

Redispersion of settled MMMF can give rise to localized concentrations of coarse fibres which may be inhaled. Inhalation of large amounts of MMMF are known to give respiratory tract irritation [7]. As a rule of thumb one can state that fibres with diameters larger than 3 μm (non-respirable) will deposit in the upper airways and bronchi, whereas respirable fibres penetrate deep into the lung and can reach the alveoli. No information is available regarding a more detailed size-specific irritation potential.

It follows from this discussion that coarse fibres, i.e. with diameters exceeding 3–4 μm, and especially fibres settled onto surfaces are an important factor to be considered in the indoor environment.

The present paper discusses the relative effect of ventilation vs cleaning on controlling exposure to MMMF in the indoor environment. Simplifying assumptions have to be made; in particular that fibres once settled are not redispersed.

In a discussion of the significance of ventilation for the sedimentation of particles, MMMF as a contaminant may be unique. The reason is that it turns out that the importance of settling as compared to ventilation as a removal mechanism of airborne fibres changes drastically over the diameter interval from 5–10 μm, the same interval in which the skin irritation potential changes from non-existent to maximum.

THE FIBRE ELIMINATION PROBLEM

The effect of ventilation and sedimentation on concentration and size distribution of airborne particles has received attention over the years with regard to bacteria—including their settling. The concentration of fibres of any diameter and length will likewise depend on the source type and strength as well as the dilution ventilation rate and the sedimentation rates for different particle size, shape and density.

The average residence time in the air environment of entering fibres is an illustrative measure of the combined effects of ventilation and sedimentation and will thus be calculated using a simple, existing mathematical model.

The overall air quality condition in the interior of buildings is virtually not constant round the clock, but is influenced by changes in the strength of the sources caused by changes in movements and activity in the building. In addition, changes in ventilation rates and turbulence in the internal air currents may cause corresponding changes in local concentrations and re-entrainment of particles from surface layers.

Multi-compartment models have been developed [8]. The mixing is modelled as the combined transport of pollutants by the net flow of ventilation air through the compartment as well as the intra-compartment mixing caused by eddies. These models do not work for particles having large settling velocities compared to the average velocity of ventilating air through the compartments. Exchange of large particles due to eddies will depend on local air velocity, in close proximity to particle sources.

The proper modelling thus gets very complex. However, the use of complex models may only be of limited benefit to an understanding of the present problem, partly because one important factor, the redispersion of settled dust, is not well characterized theoretically. For simplicity we will thus only consider the well-known model of an enclosed space with constant sources and elimination rates, no resuspension and with uniform fibre distribution in the air (one-compartment model).

The mass balance equation of fibres for the volume of space W (m^3) loaded by a fibre generation rate $G(v)$ (f h^{-1}) of fibres with settling speed v (m h^{-1}) and ventilated by air flow rate Q (m^3 h^{-1}) is given by

$$\frac{\mathrm{d}C}{\mathrm{d}T} = \frac{G}{W} - N(C-C') - \frac{vC}{H} \quad (1)$$

where

C = fibre concentration in the room air (f m^{-3})
C' = fibre concentration in the ventilating air (f m^{-3})
N = Q/W, ventilation rate (h^{-1})
H = ceiling height (m).

The solution of equation (1) for constant G and C' is:

$$C(v,t) = \frac{H(G/W+NC')}{(v+NH)} + \frac{C(v,0)-H(G/W+NC')}{(v+NH)} \exp\left[-(v+NH)t/H\right]. \quad (2)$$

For $t \to \infty$ (steady-state concentration) one has

$$C(v,\infty) = \frac{(G/W+NC')H}{(v+NH)}. \quad (3)$$

The following simplifying assumptions have been made:

(i) The concentration and size distribution of MMMF incoming with the ventilating air is constant.
(ii) The number of fibres on the surfaces of the MMMF-containing material ready to take off for entrainment is constant, which means that any aging effect or effect of climatic changes is not taken into account.
(iii) Convection currents and turbulent diffusion in the enclosed space maintain a uniform concentration of fibres, but the velocities are not so high as to redisperse settled fibres.
(iv) The dust is assumed to be dispersed into the space evenly distributed. Except close to the source, this is a fair approximation owing to (iii).
(v) Fibre removal is only by sedimentation. Brownian diffusion and deposition of larger fibres onto floor, walls and ceiling by turbulent diffusion is neglected.

The average residence time θ of a contaminant is defined as

$$\theta = \frac{\int_0^\infty tC(t)\,dt}{\int_0^\infty C(t)\,dt} \quad (4)$$

where $C(t)$ is the concentration following a pulse injection at time $t = 0$ [8]. For $C(v, t)$ given by formula (1)

$$\theta(v) = \frac{H}{(NH+v)}. \quad (5)$$

Notice that C' is of no importance, since θ is the residence time of individual fibres.

The settling speed v (m h^{-1}) of fibres can be approximated by [9]

$$v = kD^rL^s. \quad (6)$$

We will use the expression,

$$v = 0.18\frac{\rho}{\rho_0}D^{1.73}L^{0.267}\,\mathrm{m\,h^{-1}} \quad (7)$$

where ρ_0 is unit density, and D and L are in μm.

The average residence time for the fibres having an aspect ratio of $L/D = 20$ and a density 2.5 g cm^{-3} in the airborne state will be given by equation (4) and is shown for air change rates $N = 0.25$, 0.5, 1, 2, 4, 8 and 16 (ACH) in Fig. 1 in a log–log diagram with residence time calculated in seconds. The ceiling height is assumed to be 2.80 m in the example as a common value in day-care institutions and schools. For fibres with diameter larger than 10 μm settling is apparently the predominant mechanism of elimination from the airborne state, which is executed within less than a few minutes.

For the smallest and respirable fibres the dilution ventilation rate is dominating, under the assumption that the ventilating air is clean air.

It is also illustrative to calculate the ratio E—the rate of removal by sedimentation divided by the rate of removal by ventilation (see Fig. 1):

$$E = \frac{V}{NH}. \quad (8)$$

Ventilation rates less than 4 ACH have virtually no effect on fibres with diameters exceeding 10 μm, and ventilation rates less than 1.0 ACH have very little effect on the removal of fibres with diameters between 3 and 10 μm compared to the removal of these fibres from the room air by sedimentation. These fibres are then after settling on surfaces available for skin contact or local redispersion unless they are constantly and efficiently removed by cleaning. This underlines the fact that if accumulation is allowed to occur, even the load from a weak source may be a cause of complaints about the indoor environment.

DISCUSSION

The knowledge of low-level dosage effects related to MMMF exposure is so far very limited. A number of causes of complaints about indoor climate discomfort may exist in 'sick buildings', in which most field studies have been done [10].

Meanwhile it should be pointed out that a distinction has to be made between the origin of the fibres and their size for analytical and preventive reasons when dealing with this potential indoor contaminant. Most airborne MMMF have diameters less than 3 μm. Fibres with diameters less than 0.2 μm are not detectable by phase-contrast optical microscopy (PCOM) analysis of air samples, but

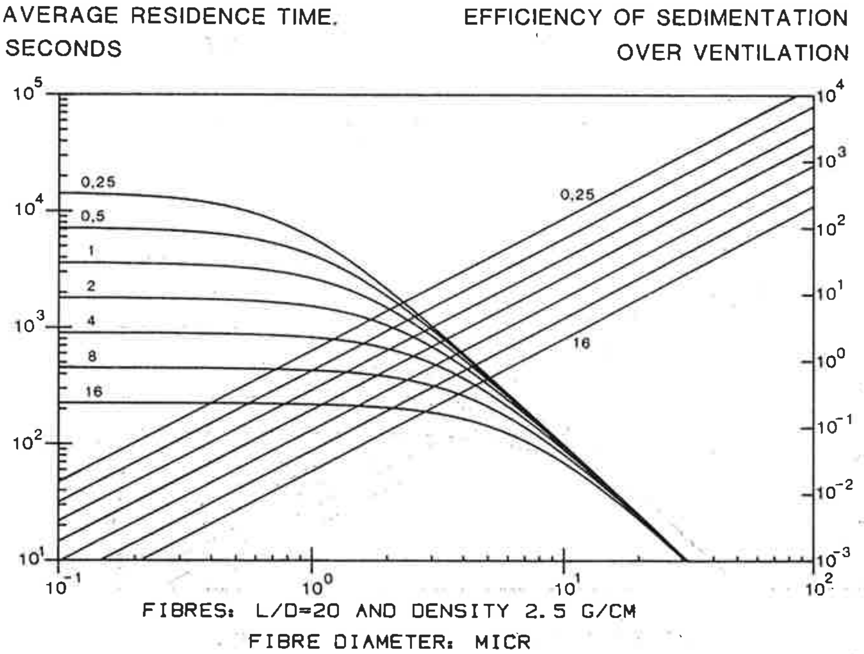

Fig. 1. Average residence time for fibres having aspect ratio 20 for various ventilation rates N (left scale). Also shown are the ratios of removal rate by sedimentation divided by removal rate by ventilation (right scale).

they constitute only a minor fraction [11]. Concentrations determined by PCOM are thus good indicators of the presence of thin fibres. It is essential that PCOM is combined with polarization techniques, since typically less than 1% of the fibres are MMMF [3].

The preventive measure of reducing exposure to respirable fibres is partly to remove or reduce the sources or to use dilution ventilation with clean air. However, ventilation rates in modern energy-efficient buildings without mechanical ventilation and a tight building envelope may have natural infiltration rates in day-care institutions well below 0.5 ACH [12]. Even in mechanically ventilated schools and offices may ventilation rates normally be lower than or equal to 4 ACH.

The simple theoretical calculations have shown that these ventilation rates have no effect whatsoever on large fibres and 'shots'. Regular and efficient cleaning of all surfaces and objects which may be touched or disturbed regularly or occasionally is thus the only preventive measure, if the sources can not be reduced or removed. Visual inspection of surface contamination and detection and quantification of MMMF in this settled dust should always supplement the taking of air samples during investigations of possible causes of eye, skin and upper respiratory irritation, when the possible presence of MMMF can not be excluded.

Methods for monitoring surface contamination have been in use in other fields in which experience is already present, such as wipe testing of toxic substances and radionucleides [13]. For monitoring MMMF, use of finger- or foot-print lifters, which are special sticky foils used for forensic purposes are superior. They have excellent adhesive and optical properties and the foils can be studied directly in an optical microscope at magnifications of 500 ×, or higher [3].

So far the knowledge of emission of mineral fibres and particulates from various materials in common use for interior surfaces is not established, but the result of a multi-lab research project in Denmark dealing with methods for testing fibre emission from ceiling boards is in preparation [14]. An erosion test has been described for factory-made air ducts and connectors, but only for macroscopic particles [15]. Fibre entrainment from loose fibre materials, especially in new air filters, and the aging of the filters in use as a reducing factor has been described [16]. The aging effect may, however, be working in the opposite direction in air ducts and on all surfaces not open for inspection and cleaning as well as ceiling and wall boards, where potential for physical damage has also to be taken into account.

CONCLUSION

Man-made mineral fibres with diameters exceeding 3–5 μm and especially fibres settled onto surfaces are important factors to be considered in the indoor environment.

Direct transfer of such fibres upon contact with contaminated surfaces or fabrics may cause skin irritation. Fibres transferred via the fingers to the face, eyelids and eyes can cause irritation. They can be redispersed locally and inhaled before they settle out again. They will deposit in the upper airways. The size and concentration below which no airway irritation symptoms occur are not known.

Ventilation rates less than 4 ACH have virtually no effect on fibres with diameters exceeding 10 μm and rates less than 1 ACH have very little effect on the removal of fibres with diameters down to 3 μm. The only preventive measures are to remove, reduce or avoid sources. If this can not be obtained then regular and efficient cleaning will be the only preventive measure.

Detection and quantification of MMMF on surfaces should always supplement air sampling during investigation of possible causes of skin, eye and upper airway irritation, when the presence of MMMF can not be excluded.

The concentration of airborne, respirable (diameter ≤ 3 μm) MMMF can be controlled by ventilation. However, at very low infiltration rates (0.25 ACH) the efficiency of sedimentation can exceed the efficiency of ventilation in removing the fibres for diameters as low as 1 μm.

REFERENCES

1. A. Rindel. E. Bach, N. O. Breum, C. Hugod, A. Nielsen and T. Schneider, Health aspects of using mineral wool ceiling boards in nursery schools (in Danish with an English summary). *Arbejdsmiljøfondet, Vesterbrogade* **69**, Copenhagen V. (1985).
2. K. E. Alsbirk, M. Johansen and R. Petersen, Ocular symptoms and exposure to mineral fibres in boards for sound-insulation of ceilings (in Danish with English summary). *Ugeskr. Læger* **145**, 43–7 (1983).
3. T. Schneider, Man-made mineral fibres and other fibres in the air and in settled dust. *Envir. Int.* to be published.
4. P. A. Possick, G. A. Gellin and M. M. Key, Fibrous glass dermatitis. *Am. ind. Hyg. Ass. J.* **31**, 12–15 (1970).
5. J. Lucas, The cutaneous and ocular effects resulting from worker exposure to fibrous glass. In *Occupational Exposure to Fibrous Glass*, Symposium proceedings, University of Maryland (1974). USDEH, NIOSH (April 1976).
6. J. M. C. Cuipers, E. Bleumink and J. P. Nater, Dertamologisch Aspekte der Glassfaserfabrikation. *Berufsdermatosen* **23**, 143–154 (1975).
7. T. H. Milby and C. R. Wolf, Respiratory tract irritation from fibrous glass inhalation. *J. occup. Med.* **11**, 409–410 (1969).
8. M. Sandberg, The multichamber theory reconsidered from the viewpoint of air quality studies. *Bldg Envir.* **19**, 221–233 (1984).
9. P. Y. Yu and J. W. Gentry, Experiment and interpretation for fiber size distribution from penetration measurements. *J. Aerosol Sci.* **16**, 3–117 (1985).
10. J. Stolwijk, The "sick building" syndrome, *Proc. Int. Conference on Indoor Air Quality and Climate*, Stockholm, Vol. 1, pp. 23–30 (1984).

11. T. Schneider, J. Skotte and P. Nissen, Man-made mineral fibre size fractions and their interrelation. *Scand. J. Work. Envir. Hlth* **11**, 117–122 (1985).
12. G. R. Lundqvist, M. Iversen and J. Korsgaard, Indoor climate in low-ventilated day-care institutions. *Envir. Int.* **8**, 139–142 (1982).
13. E. B. Sansone and N. W. Slein, Redispersion of indoor surface contamination: a review. *J. Hazardous Mat.* **2**, 347–361 (1977/78).
14. Teknologirådet, Research project No. 1984–133/508–84.332, National Agency of Technology, Tagensvej 135, Copenhagen (1984).
15. Factory-made air ducts and connectors, Standard for Safety, Underwriters Laboratories, Melville NY (1984).
16. N. A. Esmen, D. Whittier, R. A. Kahn, T. C. Lee, M. Sheehan and N. Kotsko, Entrainment of fibers from air filters. *Envir. Res.* **22**, 450–465 (1980).