Ann. occup. Hyg., Vol. 47, No. 8, pp. 653–669, 2003
Published by Oxford University Press
DOI: 10.1093/annhyg/meg090

Cellulosic Building Insulation versus Mineral Wool, Fiberglass or Perlite: Installer's Exposure by Inhalation of Fibers, Dust, Endotoxin and Fire-retardant Additives

**N. O. BREUM[1]*, T. SCHNEIDER[1], O. JØRGENSEN[1],
T. VALDBJØRN RASMUSSEN[2] and S. SKIBSTRUP ERIKSEN[2]**

[1]*National Institute of Occupational Health, Lersoe Parkalle 105, DK-2100 Copenhagen;* [2]*Danish Building and Urban Research, Dr. Neergaardsvej 15, DK-2970 Hoersholm, Denmark*

Received 3 February 2003; in final form 5 June 2003

A task-specific exposure matrix was designed for workers installing building insulation materials. *A priori*, a matrix element was defined by type of task (installer or helper), type of work area (attic spaces or wall cavities) and type of insulation material (slabs from mineral wool, fiberglass or flax; loose-fill cellulosic material or perlite). In the laboratory a mock-up (full scale) of a one-family house was used for simulated installation of insulation materials (four replicates per matrix element). Personal exposure to dust and fibers was measured. The dust was analyzed for content of endotoxin and some trace elements (boron and aluminum) from fire-retardant or mold-resistant additives. Fibers were characterized as WHO fibers or non-WHO fibers. In support of the exposure matrix, the dustiness of all the materials was measured in a rotating drum tester. For installers in attic spaces, risk of exposure was low for inhalation of dust and WHO fibers from slab materials of mineral wool or fiberglass. Slab materials from flax may cause high risk of exposure to endotoxin. The risk of exposure by inhalation of dust from loose-fill materials was high for installers in attic spaces and for some of the materials risk of exposure was high for boron and aluminum. Exposure by inhalation of cellulosic WHO fibers was high but little is known about the health effects and a risk assessment is not possible. For the insulation of walls, the risk of installers' exposure by inhalation of dust and fibers was low for the slab materials, while a high risk was observed for loose-fill materials. The exposure to WHO fibers was positively correlated to the dust exposure. A dust level of 6.1 mg/m^3 was shown to be useful as a proxy for screening exposure to WHO fibers in excess of 10^6 fibers/m^3. In the rotating drum, slabs of insulation material from mineral wool or fiberglass were tested as not dusty. Cellulosic loose-fill materials were tested as very dusty, and perlite proved to be extremely dusty.

Keywords: cellulose; dustiness; fiber; insulation; mineral

INTRODUCTION

Modern industry uses both naturally occurring and man-made mineral fibers in large quantities. The property of finely divided fibers of low density to occupy a great volume has made them particularly useful in insulation where air trapped within the fibrous mass provides the main barrier to heat transfer. Comprehensive data are available on heat transmission and other physical properties of various insulation materials, enabling comparisons to be made. In contrast, data are sparse for occupational exposure to dust by inhalation, and by deposition in eyes and on skin during the installation of these materials, which hampers valid comparison of exposures. Therefore, the objective of this study was to establish a task-specific exposure matrix for installers of common insulation materials and to assess the risk of exposure by inhalation of dust. Dustiness of a material is defined as the tendency of dry materials to liberate dust into the air when handled under specific conditions (BOHS, 1985). Dustiness is an important

---

*Author to whom correspondence should be addressed. Present address: National Working Environment Authority, Hobrovej 461, DK-9200 Aalborg SV, Denmark. E-mail: nob@arbejdstilsynet.dk governing parameter for occupational exposure by inhalation of dust. Thus, dustiness of the materials was tested in the laboratory using a standardized rotating drum dustiness tester. The purpose was twofold: (i) to obtain additional information on the composition of dust to be used for risk assessment of exposure by inhalation of dust; and (ii) to assess the relation between the results of the dustiness test and dust concentrations measured in the breathing zone of installers.

MATERIALS AND METHODS

Task-specific exposure matrix

Insulation materials. The study included different types of insulation materials (and installation method) as listed in Table 1.

Work areas. At construction sites, several sources in concert may add airborne dust, and more often than not insulation workers are not exposed just to dust from the insulation material being installed. The exposure by inhalation of dust is governed by several factors including the emission rate of contaminants, distance from the sources, time of occupancy, size of the room and air exchange rate. Thus, it is difficult (if not impossible) to keep work area conditions identical throughout sampling campaigns in the field. As an alternative approach for the study a full-scale mock-up of a one-family terrace house (one-storey) was considered useful for testing in the laboratory (Fig. 1). To keep identical weather conditions (calm air) throughout the study period (June–July) the mock-up was kept in a large laboratory hall (volume 10^4 m^3) with no mechanical ventilation and ‘low’ natural ventilation (all doors closed) while an insulation task was in progress. The air temperature and the level of air humidity were considered to be similar to the conditions outdoors. It is noted that full-scale testing of mineral wool products (slab materials) in the laboratory is a well-established technique to examine product improvements in terms of exposure by inhalation of dust (Dybro Juhl *et al.*, 1998). The mock-up was designed to allow the insulation of two different types of building components: the attic and cavities in the walls. For the study, each component was split into four identical sections to allow replication ($n = 4$) of the insulation; the attic was split by building foil (plastic) suspended from the sloping beams. When the insulation of the mock-up was completed all the installed material was removed (by the laboratory staff) to allow the installation of another material. The mock-up was designed for easy removal of the installed insulation, and further details including specifications of cleaning the mock-up and the laboratory are given elsewhere (Breum *et al.*, 2002). It is noted that the study objective did not include personal exposure in removal of the insulation or in cleaning the mock-up and the laboratory.

Table 1. Type of insulation material and installation method

Type of insulation material	Supplier	Installation method	Comment
Cellulose from paper (CP)	A	Loose-fill (wet blowing[a])	Shredded (‘fiberized’) post-consumer recycled paper[b]
Cellulose from paper (CP)	A	Loose-fill (dry blowing[a])	Shredded (‘fiberized’) post-consumer recycled paper[b]
Cellulose from paper (CP)	B	Loose-fill (dry blowing[a])	Shredded (‘fiberized’) post-consumer recycled paper[b]
Cellulose from paper (CP)	C	Loose-fill (dry blowing[a])	Shredded (‘fiberized’) post-consumer recycled paper[b]
Cellulose from wood (CW)	D	Loose-fill (dry blowing[a])	Defibrillated cellulose fiber from wood[b]
Perlite	E	Loose-fill (pouring)	
Fiberglass	F	Rolls pre-cut to fit the stud bays	Non-faced[c]
Fiberglass	F	Slabs	Non-faced[c]
Mineral wool[e]	G	Slabs	Non-faced[c]
Flax	H	Slabs	Non-faced[c,d]
Flax	I	Slabs	Non-faced[c]

[a] The material is dry and blown through a hose into place. For some applications (attic insulation) it is possible to fit an array of nozzles at the outlet of the hose to add water droplets to the insulation material, a practice (wet blowing) that is popularly believed to reduce dust concentrations

[b] The material also contains additives for, for example, fire or mold resistance. The additives (e.g. borates, ammonium phosphate and aluminum hydroxide) are added as dry powders to the dry material, and the process does not result in chemical bonding between the additives and the cellulose. The proportions of these additives are typically 15–30% by weight.

[c] For special applications, some insulation materials are supplied with a vapor barrier facing. The material for this study had no such facing.

[d] Ammonium sulfate (8% on weight basis) as fire-retardant chemical.

[e] The newly developed high-alumina, low-silica (HT) stone (rock) wool fiber with increased biosolubility (IARC, 2002).

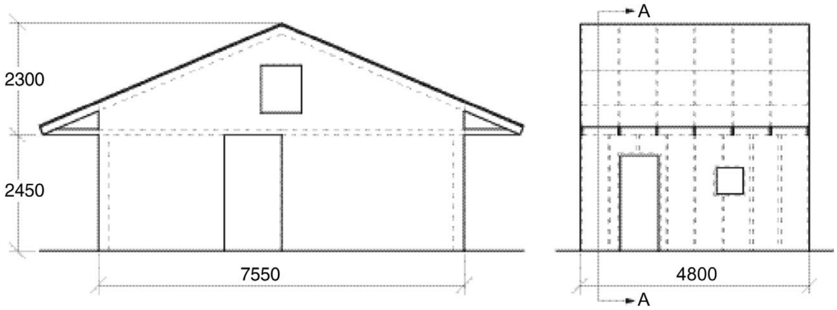

Fig. 1. Cross sections of the mock-up (dimensioning given in millimeters). Except for mineral wool or perlite, access to the attic space was by a hatch (see cross-section A–A, on the left) in the front gable wall and by a hatch in the back gable wall. For mineral wool or perlite, further access was allowed by openings in the roof surface.

Table 2. Tasks of the crew (helper and installer) installing insulation materials in attic spaces or in walls

Type of insulation material	Tasks of the helper	Tasks of the installer
Loose-fill materials		
Cellulose (CP or CW)	The helper (the 'feeder') cuts open the bags of insulation material and dumps the contents into the hopper of the blowing machine (outside the laboratory). The loose wool is fluffed in the blower and then passed through a hose to its point of application.	The flow and distribution of material is controlled through the use of a regulator on the end of the hose. The insulation material is distributed directly between the rafters of the attic to a specified minimum depth and weight or into holes drilled in the outside walls.
Perlite	The material was delivered in big bags, and by crane inside the laboratory the helper hoisted the bags into the position of delivery.	The bags were emptied from the bottom. The installer directed the flow of material and his breathing zone was always close to the flow of falling material.
Slab materials		
Fiberglass (rolls)	Inside the laboratory the helper cuts open the rolls (sealed in plastic) and takes the rolls to the attic.	The rolls were used for attic insulation only. The insulation was precut to fit the stud bays. However, some cutting was required to fit non-standard spaces.
Fiberglass, mineral wool or flax	Inside the laboratory the helper cuts open the batts (sealed in plastic) and with a utility knife the batts are cut to fit non-standard spaces. The helper takes the insulation material to the installer.[a]	For insulation of walls the batts were held in position by friction. For insulation of the attic some cutting was required to fit non-standard spaces.

[a] For mineral wool the crew was just one person doing on his own all the tasks of a helper and an installer.

Tasks. The suppliers of the insulation materials selected the installation crews (crew A–I; Table 1) on their own. In general a crew had two members: an installer and a helper. An approach of narrowly defined tasks (Table 2) was taken, and there was no cross-over in tasks, i.e. installers and helpers did not switch tasks during the study. Attic or wall insulation was replicated ($n = 4$). To minimize cross-contamination from one replicate to another, sufficient time (see below) between the replicates was allowed to wash-out airborne contaminants by mechanical ventilation of the laboratory. The installer and the helper were dressed in new overalls made from Tyvek so as not to compromise the results with resuspended dust from personal clothing.

Not all crews of installers had two members, and some insulation materials were installed in attic spaces but not in walls. In total the matrix contained 40 different elements (see Table 3).

Sampling and analytical methods

Personal breathing zone samples for inhalable dust and airborne fibers were collected in parallel. GSP inhalable dust samplers (Kenny *et al.*, 1997) operated at 3.5 l/min were placed near the employees' left collar and for the full task dust was collected on membrane filters (Teflon; 3 µm pore size). The collected mass was determined by weighing the filters before and after the sampling. Exposure by inhalation of endotoxin has been reported for workers processing fiberglass (Milton *et al.*, 1996), flax (Buick *et al.*, 1994) or recycled paper (Breum *et al.*, 1996). For the installer, samples from insulation of attic spaces ($n = 2$) and the wall ($n = 2$) were analyzed for endotoxin content. The dust was resuspended in 10 ml sterile, non-pyrogenic water by orbital shaking (300 r.p.m. for 15 min) at room temperature and endotoxin was analyzed in duplicate subsamples using the kinetic Limulus Amebocyte Lysate test

Table 3. Task-specific exposure matrix for inhalable dust. If possible, data are given in terms of the geometric mean (GM), a 95% confidence interval (CI) of the mean, the geometric standard deviation (GSD) and the number (n) of samples. The ratio $R_{0.95}$ is an indicator of the homogeneity of a matrix element (see text)

Type of insulation material [supplier]	Insulation of the attic							Insulation of the wall						
	Task period[a] (min)	The installer			The helper			Task period[a] (min)	The installer			The helper		
		GM (95% CI) (mg/m^3)	GSD (n)	$R_{0.95}$	GM (95% CI) (mg/m^3)	GSD (n)	$R_{0.95}$		GM (95% CI) (mg/m^3)	GSD (n)	$R_{0.95}$	GM (95% CI) (mg/m^3)	GSD (n)	$R_{0.95}$
Loose-fill materials														
Cellulose, paper [A] Wet blowing	22 (17–26)	150 (120–300)	1.2 (4)	2.5	23.3 (8.9–61)	1.8 (4)	6.9	Wet blowing was not used						
Cellulose, paper [A] Dry blowing	18 (15–20)	40 (33–47)	1.1 (4)	1.4	7.5 (4.4–13)	1.4 (4)	3.0	23 (20–30)	7.9 (2.5–24)	2.0 (4)	9.6	2.7 (1.2–5.9)	1.6 (4)	4.9
Cellulose, paper [B]	21 (18–29)	520 (450–590)	1.1 (4)	1.3	19 (9.9–35)	1.5 (4)	3.5	18 (9–39)	380 (190–730)	1.5 (4)	3.8	11 (1.3–88)	3.8 (4)	68
Cellulose, paper [C]	28 (25–30)	84 (46–150)	1.5 (4)	3.3	4.9 (1.3–18)	2.2 (4)	14	23 (17–26)	37 (30–47)	1.2 (4)	1.6	2.1 (1.2–3.6)	1.4 (4)	3.0
Cellulose, wood [D]	14 (8–17)	46 (18–120)	1.8 (4)	6.7	0.7 (0.2–2.2)	2.0 (4)	11	27 (14–41)	16 (5.6–47)	2.0 (4)	8.4	0.6 (0.1–2.5)	1.8 (4)	25
Perlite	10 (9–18)	160 (96–250)	1.4 (4)	2.6	4.5 (2.1–9.7)	1.6 (4)	4.6	8 (5–9)	98 (64–150)	1.3 (4)	2.3	4.9[a] (1.0–5.6)	– (4)	–
Slab materials														
Fiberglass, rolls [F]	16 (15–17)	1.3 (1.0–1.6)	1.1 (4)	1.6	1.1 (0.8–1.6)	1.3 (4)	2.0	Rolls were not used						
Fiberglass [F]	26 (23–27)	0.8 (0.6–1.1)	1.1 (4)	1.8	0.4 (0.2–0.9)	1.6 (4)	4.5	15 (11–25)	0.5 (0.1–2.5)	2.8 (4)	25	0.3 (0.1–0.5)	1.4 (4)	5.0
Mineral wool [G]	22 (21–26)	1.8 (0.4–7.0)	1.8 (3)	18	No helper			18 (15–20)	0.6 (0.3–1.3)	1.6 (4)	4.3	No helper		
Flax [H]	23 (20–25)	5.7 (4.5–7.2)	1.2 (4)	1.6	1.2 (0.9–1.7)	1.2 (3)	1.9	13 (10–13)	4.1 (3.0–5.7)	1.2 (4)	1.9	1.3 (0.5–3.8)	1.9 (4)	7.6
Flax [I]	38 (32–57)	8.6 (6.2–12)	1.2 (4)	1.9	3.3 (2.5–4.5)	1.2 (4)	1.8	18 (15–21)	4.6 (1.4–15)	2.1 (4)	11	2.9 (1.3–6.5)	1.7 (4)	5.0

[a] Median (range).

(kinetic-QCL endotoxin kit; BioWhittaker). A standard curve, obtained from *Escherichia coli* 055:B5-reference endotoxin, was used to measure concentrations in terms of endotoxin units (EU) per m^3 air. Except for insulation material D (cellulose, wood), one personal (the installer) sample of dust per type of cellulosic material installed in attic spaces was analyzed by ICP for content of some constituents (boron and aluminum) of common fire-retardant or mold-resistant additives (see Table 1). In the laboratory hall, GSP samplers and 'total' dust samplers (closed-face 25 mm filter cassette with a 5.6 mm diameter inlet operated at 1.9 l/min) were mounted side-by-side on a full size non-heated mannequin. The purpose of this area sampling was to determine a conversion factor $CF_{\text{Inh dust}}$ between results obtained with the two sampling methods. For a pair of samples $CF_{\text{Inh dust}}$ was defined by the relation

$$CF_{\text{Inh dust}} = C_{\text{Inh dust}}/C_{\text{Total dust}},$$

where $C_{\text{Inh dust}}$ is the concentration of inhalable dust and $C_{\text{Total dust}}$ is the concentration of 'total' dust. A GSP sampler mounted on a non-heated mannequin was used for outdoor area sampling (reference).

Open-faced 25 mm diameter cassettes (with an electrically conducting cowl) operated at 1.0 l/min were placed near the employees' right collar for the sampling of airborne fibers. An approach of full task sampling was taken, but in reality—except for insulation with fiberglass or mineral wool—grab sampling was necessary to prevent overloading of the filters. Three grab samples of different duration were taken per task and the sampling periods were chosen to ensure that at least one sample was useful for further analysis. Only one sample per task was analyzed for content of fibers, and the derived concentration of airborne fibers was, as a rough estimate, considered a full task time-weighted average. Unexpected constraints in the laboratory prevented the analysis of all the scheduled samples and the number of samples analyzed per matrix element are listed in Table 4. After sampling, the filters were rendered transparent using the acetone—triacetin method (WHO, 1996). According to the WHO method (WHO, 1996), fibers are analyzed by phase-contrast optical microscopy (PCM). However, due to the large amount of non-fibrous material causing interfering halo effects in PCM, in conjunction with the need to discriminate between fibers, polarized light microscopy (PLM) was used. Since the organic fibers were long and the concentration of especially mineral wool fibers were low, a 25×/0.50 objective was used. A calibrated ruler divided in units of 4 µm was inserted in the eyepiece for sizing. The diameter of fibers with diameters less than 4 µm was determined using a 63×/0.85 objective. All fibers wholly or partly within the field of view were counted and sized, and the bias corrected using rule G as specified in Schneider (1979). The PLM method was compared with the PCM method as specified by WHO (WHO, 1996). Two samples (Rockwool and Superglass) that formerly were in the WHO/EURO reference scheme were obtained from the Institute of Occupational Medicine, Edinburgh. All slides in the present study were counted by the same microscopist.

By definition, a particle of diameter D and length L was considered a fiber for an aspect ratio (= L/D) >3.0. Such a fiber was characterized in terms of D and L. For a density ρ, an optical diameter D, and an aspect ratio ranging from 10 to 15, the aerodynamic diameter (D_{ae}) of a fiber is (Gonda and AbdElKhalik, 1985):

$$D_{\text{ae}} = 1.6 \times D \times \sqrt{\frac{\rho}{\rho_0}}$$

where ρ_0 is unit density.

Particles were considered respirable if $D_{\text{ae}} < 7$ µm. As a rough estimate the density of mineral fibers is 2.65 g/cm^3, and from the equation above mineral fibers are respirable if $D < 3$ µm (the WHO fiber diameter criterion). In contrast to mineral fibers, the density of organic fibers is low (~0.96 g/cm^3), and from the equation above organic fibers are respirable if $D < 5$ µm. In this study, exposure by inhalation of fibers are given in terms of four different size fractions: (1) all fibers ('total' fibers), (2) WHO fibers—this fraction is all fibers of $D < 3$ µm, (3) non-WHO fibers—this fraction is all fibers of $D > 3$ µm, and (4) fibers of $D < 5$ µm.

For the statistical analysis it was considered important to obtain independent data. In order to verify that cross-contamination from one replicate to another was low, a particle counter (Grimm) placed stationary in the laboratory hall recorded the concentration of dust throughout the study. The criterion to allow the installation of a material was set at a concentration level not exceeding the concentration in the morning by >10%.

Dustiness testing

Dustiness of a material is defined as the tendency of dry materials to liberate dust into the air when handled under specific conditions (BOHS, 1985). Dustiness testing, therefore, is empirical and the test results are method dependent. A dustiness tester consists of two parts: a dust generator and a dust sampler. The present study took advantage of a well-characterized rotating drum dust generator. The all stainless steel drum (0.30 m internal diam.) rotated (40 r.p.m.) for 3 min on a horizontal axis. Air was exhausted (50 l/min) from one end of the drum (0.02 m diameter outlet opening). Filtered air at a constant level of relative humidity (50%) was delivered at ambient pressure (>50 l/min) at the inlet opening at the opposite end of the drum. Further

Table 4. Task-specific exposure matrix for WHO fibers. If possible, data are given in terms of the geometric mean (GM), a 95% confidence interval (CI) of the mean, the geometric standard deviation (GSD) and the number (n) of samples. The ratio $R_{0.95}$ is an indicator of the homogeneity of a matrix element (see text); the indicator was not estimated for data sets holding less than three observations

Type of insulation material [supplier]	Insulation of the attic						Insulation of the wall					
	The installer			The helper			The installer			The helper		
	GM (95% CI) (fibers/m^3)	GSD (n)	$R_{0.95}$	GM (95% CI) (fibers/m^3)	GSD (n)	$R_{0.95}$	GM (95% CI) (fibers/m^3)	GSD (n)	$R_{0.95}$	GM (95% CI) (fibers/m^3)	GSD (n)	$R_{0.95}$
Loose-fill materials												
Cellulose, paper [A] Wet blowing	2.5×10^{6} [a] ($2.5–2.5 \times 10^{6}$)	– (2)	–	9.5×10^{4} [a] ($9.5–9.6 \times 10^{4}$)	– (2)	–	Wet blowing was not used					
Cellulose, paper [A] Dry blowing	1.5×10^{6} [a] ($1.2–1.8 \times 10^{6}$)	– (2)	–	3.7×10^{5} [a] ($3.6–3.8 \times 10^{5}$)	– (2)	–	1.3×10^{5} [a] ($1.1–1.5 \times 10^{5}$)	– (2)	–	1.2×10^{5} [a] ($9.4–1.4 \times 10^{5}$)	– (2)	–
Cellulose, paper [B]	3.4×10^{6} [a] ($3.2–3.6 \times 10^{6}$)	– (2)	—	4.0×10^{5} [a] ($3.4–4.7 \times 10^{5}$)	– (2)	–	2.8×10^{6} ($4.7 \times 10^{5}–1.7 \times 10^{7}$)	2.1 (3)	36	1.5×10^{5} ($1.7 \times 10^{4}–1.3 \times 10^{6}$)	2.4 (3)	78
Cellulose, paper [C]	4.9×10^{6} ($3.6–6.6 \times 10^{6}$)	1.1 (3)	1.8	1.5×10^{5} [a] ($1.1–1.9 \times 10^{5}$)	– (2)	–	2.2×10^{6} ($1.0–4.8 \times 10^{6}$)	1.4 (3)	4.8	2.1×10^{4} ($1.2 \times 10^{2}–3.9 \times 10^{6}$)	8.1 (3)	3300 0
Cellulose, wood [D]	1.8×10^{6} ($3.8 \times 10^{5}–8.6 \times 10^{6}$)	1.9 (3)	23	1.2×10^{3} ($9.1 \times 10^{2}–1.6 \times 10^{3}$)	1.1 (3)	1.8	3.0×10^{5} ($6.5 \times 10^{3}–1.4 \times 10^{7}$)	4.7 (3)	2200	8.0×10^{2} [a] ($6.4–9.6 \times 10^{2}$)	– (2)	-
Perlite	No sampling for airborne fibers											
Slab materials												
Fiberglass, rolls [F]	3.6×10^{4} [a] ($3.0–4.2 \times 10^{4}$)	– (2)	–	2.0×10^{4} [a] ($1.8–2.2 \times 10^{4}$)	– (2)	–	Rolls were not used					
Fiberglass [F]	2.3×10^{4} ($8.9 \times 10^{3}–5.8 \times 10^{4}$)	1.5 (3)	6.5	2.4×10^{4} [a] ($2.1–2.7 \times 10^{4}$)	– (2)	–	5.7×10^{3} ($3.0 \times 10^{3}–1.1 \times 10^{4}$)	1.5 (4)	3.7	2.3×10^{3} ($9.8 \times 10^{1}–5.2 \times 10^{4}$)	3.5 (3)	530
Mineral wool [G]	1.6×10^{4} ($7.8 \times 10^{3}–3.2 \times 10^{4}$)	1.6 (4)	4.1	No helper			5.5×10^{3} ($4.9 \times 10^{3}–1.5 \times 10^{4}$)	– (4)	–	No helper		
Flax [H]	7.3×10^{4} ($5.6–9.4 \times 10^{4}$)	1.2 (4)	1.7	4.0×10^{4} [a] ($1.3–6.7 \times 10^{4}$)	– (2)	–	7.7×10^{3} [a] ($7.0 \times 10^{2}–1.5 \times 10^{4}$)	– (2)	–	6.8×10^{4} [a] ($5.2 \times 10^{3}–1.3 \times 10^{5}$)	– (2)	–
Flax [I]	4.3×10^{4} ($6.7 \times 10^{3}–2.8 \times 10^{5}$)	2.1 (3)	420	1.5×10^{4} [a] ($9.4 \times 10^{3}–2.0 \times 10^{4}$)	– (2)	–	1.8×10^{4} [a] ($1.6–2.0 \times 10^{4}$)	– (2)	–	1.1×10^{4} [a] ($8.1 \times 10^{3}–1.3 \times 10^{4}$)	– (2)	–

[a] Median (range).

details of the design of the drum are given elsewhere (Breum, 1999). The dust sampler was a membrane filter (Teflon; 3 µm pore size, 90 mm diameter) at the outlet of the drum. The collected mass of dust was determined by weighing the filter before and after the sampling. The dustiness (as a percentage) was estimated as the mass of dust collected in proportion to the mass of material under testing. Prior to the testing, the internal surfaces of the drum were saturated by running an initial test.

The present study includes two types of insulation materials: loose-fill and slabs (including rolls). The mass of a loose-fill material used for dustiness testing ($n = 3$) was 10 g per run. The samples for testing were drawn from the insulation material installed in the muck-up. For slab materials the volume of material per run ($n = 3$) was constant ($0.1 \times 0.1 \times 0.1$ m). For a given material the helper, with his own knife, cut the samples for testing from a slab to be installed in the muck-up. Per type of insulation material, one sample of the generated dust was analyzed for content of endotoxin. Except for material F (fiberglass) and G (mineral wool) one sample of the dust was analyzed for boron, aluminum, chromium, lead and cadmium concentration.

Statistical analysis

The data obtained were log-transformed and tested (Anderson–Darling test) for normality at a 5% level of statistical significance. Levene's test was performed for the homogeneity of variance between groups of data.

Hypotheses on differences between groups of data were tested parametrically by analysis of variance (Turkey's test for multiple comparisons) or non-parametrically (Mood's median test). MINITAB software was used for the statistical analysis (MINITAB release 10Xtra).

RESULTS

The full-scale testing period ranged from June to July and the outdoor temperature and humidity were 18–25°C and 36–59%, respectively. The outdoor concentration ($n = 6$) of inhalable dust was low: geometric mean (GM) = 0.024 mg/m^3; 95% confidence interval (CI): 0.0085–0.067 mg/m^3; geometric standard deviation (GSD) = 2.7. The data obtained on personal exposure by inhalation of dust and WHO fibers are listed in Table 3 (inhalable dust) and Table 4 (WHO fibers). Table 3 includes data on the time required to install the insulation material. In contrast to the installers of slab-materials, exposure to inhalable dust was high ($P < 0.05$) for the installers of loose-fill materials. In general, an installer was exposed to more dust than his helper, and exposure during insulation of the attic space was high compared to the insulation of a wall. A similar pattern of exposure was observed for WHO fibers but it is noted that a formal statistical test was not used owing to few observations per matrix element. The homogeneity of results within each matrix element was quantified by calculating ratios ($R_{0.95}$) between the 97.5th and the 2.5th percentile. The upper and lower limit of the 95% confidence interval was considered a rough estimate of these percentiles. The estimated ratios are included in Table 3 and Table 4. Note that $R_{0.95}$ was estimated only for matrix elements holding a 95% confidence interval.

Fibers collected on a given filter were classified as WHO fibers or non-WHO fibers. Within each class of fibers, the size distribution per filter was characterized in terms of the GM and the GSD of the diameter and the length, respectively. For a given type of insulation material, n independent samples of airborne fibers were collected, and the GM of all the independent samples is given in Fig. 2 (diameter) and Fig. 3 (length). The GM diameter of WHO fibers from loose-fill materials was small ($P < 0.001$) in comparison with fibers from the slab materials of mineral wool or fiberglass. On the other hand, the GM diameter of the non-WHO fibers from the slab materials of mineral wool or fiberglass were smaller than all the GM diameters of other types of insulation materials ($P < 0.001$). Except for flax (supplier H), the GM lengths of WHO fibers from all types of slab insulation materials were larger than of the fibers from the loose-fill materials ($P < 0.001$). The GM length of non-WHO fibers from slabs of flax (supplier I) was larger than the GM length of non-WHO fibers from all types of loose-fill materials ($P < 0.006$).

To allow the estimation of the concentration of non-WHO ($C_{\text{non-WHO}}$) fibers from the concentration of WHO fibers (C_{WHO}) a conversion factor ($CF_{\text{non-WHO}}$) per type of insulation material was calculated. For a given sample $CF_{\text{non-WHO}}$ was defined by the relation $CF_{\text{non-WHO}} = C_{\text{non-WHO}}/C_{\text{WHO}}$. Likewise, a conversion factor (CF_{Total}) was calculated to allow the estimation of the concentration of 'total' fibers (C_{Total}) from C_{WHO}. A conversion factor ($CF_{D<5\mu\text{m}}$) was also calculated to allow the estimation of the concentration of fibers of diameter <5 µm ($C_{D<5\mu\text{m}}$) from C_{WHO}. For each type of insulation material, n independent personal samples were available for the calculations, and the estimated conversion factors are listed in Table 5. The conversion factor required to obtain a valid estimate of exposure to respirable organic fibers from an exposure given as WHO fibers ranged (Table 5) from $CF_{D<5\mu\text{m}} = 1.3$ to $CF_{D<5\mu\text{m}} = 1.6$.

The estimated conversion factors $CF_{\text{Inh dust}}$ are also listed in Table 5. As observed from the table, different types of insulation materials had different conversion factors ($P = 0.01$). The factor for slab materials from flax (supplier H) was high (= 2.2); no difference ($P = 0.05$) was observed between the factors for fiberglass or mineral wool.

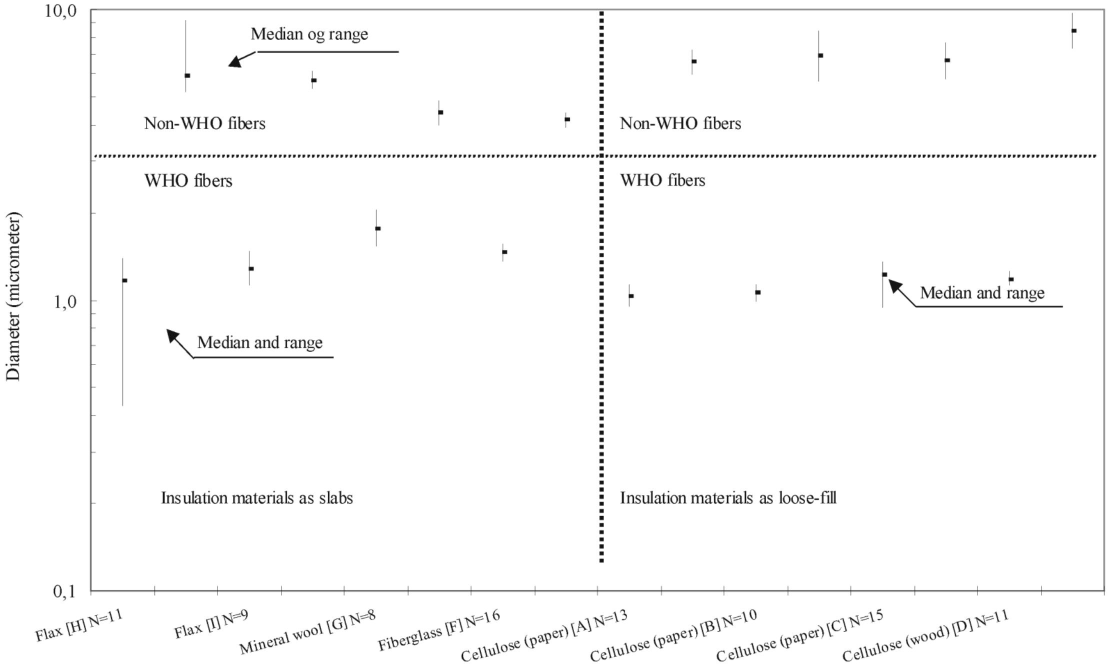

Fig. 2. The diameter of airborne WHO fibers or non-WHO fibers emitted during the installation of different types (A–D; F–I) of insulation materials (see Table 1). A diameter is given in terms of the geometric mean and the confidence interval (95%). Data are given in terms of the median and the range if the data were not log-normally distributed as observed from the Anderson–Darling test (5% level of statistical significance). The number (*n*) of independent samples are given in the figure.

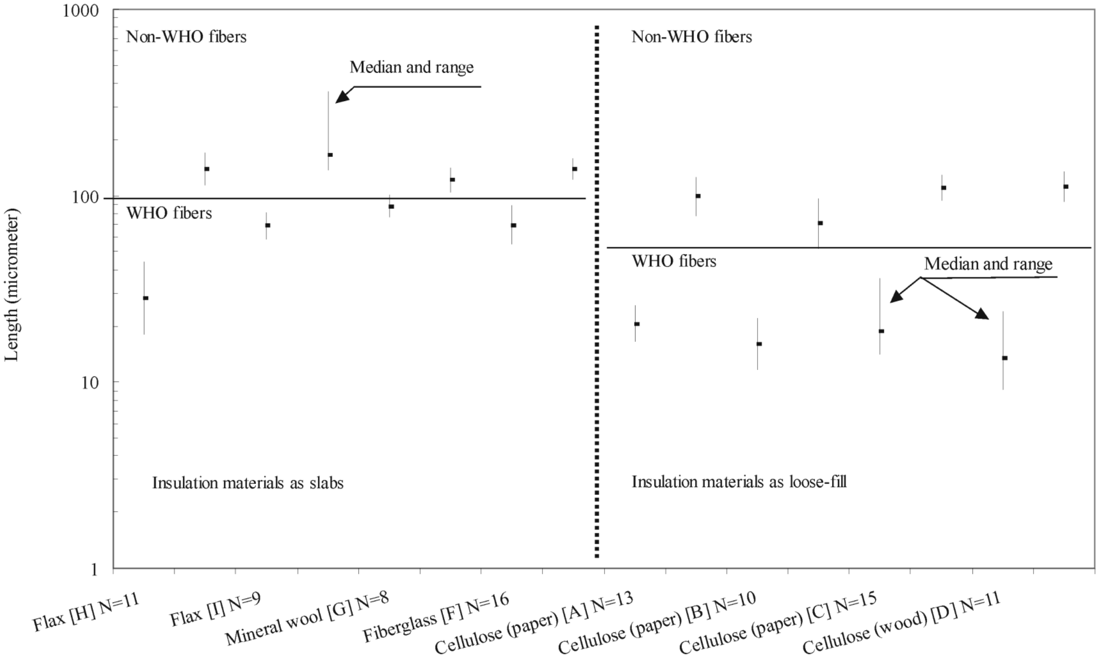

Fig. 3. The length of airborne WHO fibers or non WHO fibers emitted during the installation of different types (A–D; F–I) of insulation materials (see Table 1). A diameter is given in terms of the geometric mean and the confidence interval (95%). Data are given in terms of the median and the range if the data were not log-normally distributed as observed from the Anderson-Darling test (5% level of statistical significance). The number (*n*) of independent samples are given in the figure.

Table 5. Estimated conversion factors (CF) to allow the concentration of WHO fibers (C_{WHO}) or the concentration of ‘total’ dust ($C_{\text{Total dust}}$) to be converted to other size fractions of the collected aerosols. The factors allow C_{WHO} to be converted to the concentration of ‘total’ fibers (C_{Total}), or non-WHO fibers ($C_{\text{non-WHO}}$), or fibers of diameter <5 µm ($C_{D<5\mu m}$). For a given type of insulation material the concentrations are estimated as follows. ‘Total’ fibers: $C_{\text{Total}} = CF_{\text{Total}} \times C_{\text{WHO}}$; non-WHO fibers: $C_{\text{non WHO}} = CF_{\text{non-WHO}} \times C_{\text{WHO}}$; fibers of diameter < 5 µm: $C_{D<5\mu m} = CF_{D<5\mu m} \times C_{\text{WHO}}$. The conversion factors allow $C_{\text{Total dust}}$ to be converted to the concentration of inhalable dust ($C_{\text{Inh dust}}$) by the relation $C_{\text{Inh dust}} = CF_{\text{Inh dust}} \times C_{\text{Total dust}}$

Insulation material [supplier]	Conversion factors (CF) for fibers						Conversion factors (CF) for inhalable dust ($CF_{\text{Inh dust}}$)	
	‘Total’ fibers (CF_{Total})		Non-WHO fibers (D > 3 µm) ($CF_{\text{non-WHO}}$)		Fibers of diameter < 5 µm ($CF_{\text{D<5µm}}$)			
Loose-fill materials								
Cellulose, paper [A]	1.7[a]	1.5–1.8[b]	0.7	0.5–0.8	1.4	1.3–1.5	1.4	1.3–1.5
Wet or dry blowing	1.2[c]	13[d]	1.5	13	1.1	13	1.1	4
Cellulose, paper [B]	1.8	1.4–2.2	0.7	0.4–1.1	1.3	1.2–1.5	1.5	1.1–1.9
	1.4	10	2.1	10	1.1	10	1.2	4
Cellulose, paper [C]	1.6	1.5–1.8	0.6[e]	0.4–0.8[f]	1.3	1.3–1.4	1.6	1.3–1.9
	1.2	15	–	15	1.1	15	1.1	4
Cellulose, wood [D]	1.9	1.7–2.2	0.9	0.7–1.2	1.4	1.3–1.5	1.6	1.1–2.4
	1.2	11	1.6	11	1.1	11	1.3	4
Perlite [E]	No sampling of airborne fibers						1.7	1.5–1.9
							1.1	4
Slab materials								
Fiberglass [F]	1.6	1.5–1.8	0.6	0.5–0.7	1.5	1.4–1.7	1.0	0.7–1.4
	1.2	16	1.5	16	1.2	16	1.2	4
Mineral wool [G]	2.0	1.6–2.5	1.0	0.6–1.5	1.9	1.5–2.4	1.1	0.3–4.0
	1.3	8	1.7	8	1.3	8	2.2	4
Flax [H]	2.4	2.0–2.9	1.3	1.0–1.8	1.6[5]	1.5–3.0[6]	2.2	1.3–3.7
	1.3	10	1.5	10	–	10	1.4	4
Flax [I]	2.1	1.8–2.4	1.1	0.8–1.4	1.6	1.4–1.8	1.4	1.1–1.7
	1.2	9	1.5	9	1.2	9	1.2	4

[a] Geometric mean.
[b] Confidence (95%) interval of the mean.
[c] Geometric standard deviation.
[d] Number of observations.
[e] Median.
[f] Range.

Monitoring programs for airborne fibers impose a costly and time-consuming analytical burden. It was therefore investigated if inhalable dust could be used as a proxy for WHO fiber exposure. The present study included $n = 84$ pairs of personal sampling in parallel with ‘total’ fibers and inhalable dust. The data and the linear regression ($r^2 = 0.74$) with prediction interval (95% confidence level) is given in Fig. 4. At present, the Danish occupational exposure limit (OEL) for man-made mineral fibers is 10^6 WHO fibers/m^3 (Arbejdstilsynet, 2000). For a dust concentration of 6.1 mg/m^3, the prediction interval of the regression model ranges from 6.0×10^3 to 1.0×10^6 fibers/m^3. For the screening of occupational exposure to WHO fibers by proxy, a screening dust level (SLV) of 6.1 mg/m^3 is suggested. Four-fold table analysis was used for the estimation of the sensitivity, the specificity, the validity and the predictive values of this screening test. The estimates are given in Table 6, which also includes the definitions of the test characteristics. As observed from Table 6, the performance (sensitivity) of the screening test was high in terms of the classification of true non-compliance fiber exposures. On the other hand, the performance (specificity, SP) was less impressive in terms of the classification of true compliance fiber exposures—it has to be expected that 26% [= 100 × (1 –SP)] of a set of samples would classify a non-compliance fiber exposure although the true exposure is below the OEL. The predictive value of the screening test was high (= 1.0) for dust concentrations below the SLV (= 6.1 mg/m^3), while the performance was less impressive for concentrations above the SLV. It has to expected that 47% of the samples exceeding the SLV in reality may originate from situations of low exposure to WHO fibers, but in the screening these situations are classified as non-compliance exposures (false positive).

Some samples of inhalable dust collected for the installer were analyzed for content of endotoxin and the obtained exposure levels are listed in Table 7. For an installer, the exposure to endotoxin was significantly ($P = 0.01$) influenced by the type of insulation material. The exposure was high for the installation

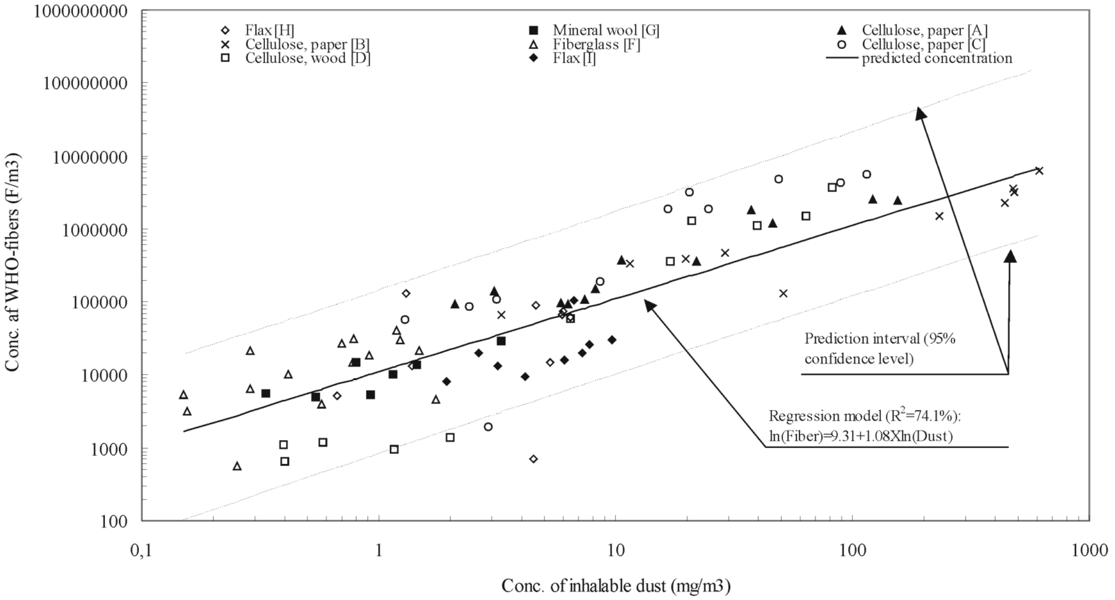

Fig. 4. The concentration of WHO fibers versus the concentration of inhalable dust for the installation of different types (A–D; F–I) of insulation materials (see Table 1).

Table 6. Four-fold table analysis of screening the concentration of airborne WHO fibers (C_{WHO}) by the concentration of inhalable dust (C_{Dust}). The screening limit value (SLV) for inhalable dust is 6.1 mg/m^3 (see the text) and the occupational exposure limit (OEL) for WHO fibers is 10^6 fibers/m^3. The number of observations (samples) meeting the criteria of the table are n_1, n_2, n_3 and n_4. The overall number of samples is $n_1 + n_2 + n_3 + n_4 = 84$

Condition of exposure to WHO fibers as estimated from the screening test	True condition of exposure to WHO fibers		
	Non-compliance: C_{WHO}/OEL > 1.0	Compliance: C_{WHO}/OEL < 1.0	
Non-compliance: C_{Dust}/SLV > 1.0	$n_1 = 19$	$n_2 = 17$	$n_1 + n_2 = 36$
Compliance: C_{Dust}/SLV < 1.0	$n_3 = 0$	$n_4 = 48$	$n_3 + n_4 = 48$
	$n_1 + n_3 = 19$	$n_2 + n_4 = 65$	$n_1 + n_2 + n_3 + n_4 = 84$

Sensitivity (SE) of the screening test: SE = $n_1/(n_1 + n_3) = 1.0$	Predictive value for cases of C_{Dust}/SLV > 1.0: $n_1/(n_1 + n_2) = 0.53$
Specificity (SP) of the screening test: SP = $n_4/(n_4 + n_2) = 0.74$	Predictive value for cases of C_{Dust}/SLV < 1.0: $n_4/(n_4 + n_3) = 1.0$
Validity (VA) of the screening test: VA = SE + SP=1.74	

of slabs from flax (supplier I); in contrast, exposure was low for the installation of slabs from mineral wool. In addition, the table lists data on the installer's exposure by inhalation of some chemical constituents of the dust. The exposure was, as a rough estimate, calculated as the mean exposure to dust in insulation of attic spaces (Table 4) times the content (as a percentage) of the chemicals in the dust. For some cases of this calculation the percentage of chemical constituents was obtained from samples of dust produced in the laboratory (dustiness testing) or from the literature (see Table 8).

The estimated dustiness of the different types of insulation materials is listed in Table 8. In addition, the table includes data on endotoxin content of the dust (endotoxin units per mg of dust) and, as a percentage, some chemical constituents in the dust collected from the dustiness testing. Among the loose-fill insulation materials, perlite was the most dusty, and flax (supplier H) was the most dusty among the slab materials ($P = 0.016$). Per type of insulation material, the mean exposure to dust for the installer working in attic spaces (Table 3) was plotted against the dustiness (medians in Table 8) of the material. For a group of insulation materials (slab or loose-fill) there is a tendency, as estimated visually from Fig. 5, for the exposure to be positively correlated to the dustiness.

The results show that installation of insulation materials may involve exposure by inhalation of a

Table 7. Personal exposure to inhalable endotoxin for installers of different types of insulation materials. The table includes data on exposure (inhalable fraction) to some trace elements (boron and aluminum) of common fire-retardant or mold-resistant additives. In addition the exposure to other trace elements (chromium, lead and cadmium) is given. The listed exposure is for installers working in attic spaces

Insulation material [supplier]	Endotoxin (EU/m^3)				Boron (mg/m^3)	Aluminum (mg/m^3)	Chromium (µg/m^3)	Lead (µg/m^3)	Cadmium (µg/m^3)
	GM[a]	CI[b]	GSD[c]	*n*[d]					
Loose-fill materials									
Cellulose, paper [A] Wet blowing	270[e]	220–320[f]	–	2	0.33	9.1	4.9	2.4	0.3
Cellulose, paper [A] Dry blowing	130	62–270	1.6	4[g]	0.087	2.4	1.3	0.6	0.3
Cellulose, paper [B]	240	82–680	2.0	4[g]	5.7	42.3	0.8	4.1	0.2
Cellulose, paper [C]	110	51–220	1.6	4[g]	0.92	0.1	0.09	2.7	0.6
Cellulose, wood [D]	100	49–210	1.6	4[g]	0.013	0.01	0.2	0.6	0.3
Perlite [E]	130	25–650	2.8	4[g]	0.005	0.1	0.4	0.3	0.04
Slab materials									
Fiberglass, rolls [F]	150[e]	35–260[f]	–	2	0.028	0.05	–	–	–
Fiberglass [F]	62[e]	<0.01–120[f]	–	3[g]	0.018	0.03	–	–	–
Mineral wool [G]	2.3	0.01–56	7.4	4[g]	0.004	0.1	0.5	0.04	0.02
Flax [H]	170	39–720	2.5	4[g]	0.006	0.06	0.05	0.08	0.3
Flax [I]	1300	220–8200	3.1	4[g]	0.94	0.1	0.2	1.1	2.6

[a] Geometric mean.
[b] Confidence interval (95%) of the mean
[c] Geometric standard deviation.
[d] Number of samples.
[e] Median.
[f] Range.
[g] Two of the samples were collected for the insulation of the walls.

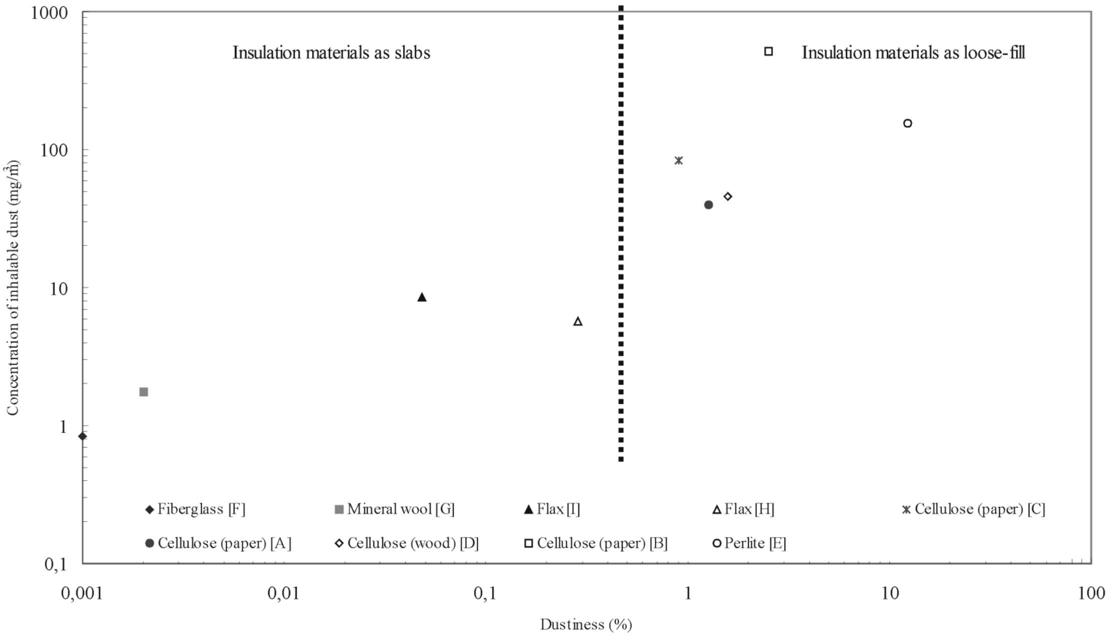

Fig. 5. The exposure to dust during the installation of different types (A–I) of insulation materials in attic spaces versus dustiness of the materials.

complex mixture of air contaminants. For risk assessment, the exposure of specific contaminants were compared to the corresponding Danish (Arbejdstilsynet, 2000) OELs. For this study the OEL of 3 mg/m^3 for non-specific organic 'total' dust was used for dust from cellulosic materials from paper or flax. For dust from wood, the OEL of 2 mg/m^3 'total' dust (wood) was used. For WHO fibers of mineral wool or fiber-

Table 8. The dustiness of different types of insulation materials. The table includes data on the endotoxin content of the dust [endotoxin units (EU) per mg of dust] and, as a percentage, some chemical constituents of the dust

Insulation material [supplier]	Dustiness %			Endotoxin (EU/mg)	Boron (%)	Aluminum (%)	Chromium (%)	Lead (%)	Cadmium (%)
	M[a]	R[b]	*n*[c]						
Loose-fill materials									
Cellulose, paper [A]	1.3	1.3–1.4	3	6.0 [7.7][d]	1.4 [0.2][d]	2.8 [6.0]*	0.003	<0.002	<0.0003
Cellulose, paper [B]	2.5	2.5–2.8	3	0.4 [0.6][d]	1.2 [1.1][d]	4.4 [8.2]	0.0002	<0.0008	<0.0002
Cellulose, paper [C]	0.9	0.6–1.0	3	5.7 [1.9][d]	5.1 [1.1] [d]	0.08 [0.1]*	0.0001	<0.003	<0.0006
Cellulose, wood [D]	1.6	1.5–1.8	3	0.7 [3.6][d]	0.03	0.01	0.0004	<0.001	<0.0003
Perlite [E]	12.3	12.1–12.9	3	0.3 [2.1][d]	0.004	0.08	0.0002	<0.0002	<0.00004
Slab materials									
Fiberglass [F]	<0.001	<0.001–0.003	3	1.1 [98][d]	2.2[e]	3.7[e]	–	–	–
Mineral wool [G]	0.002	<0.001–0.003	3	<0.3 [3.4][d]	<0.2[e]	7.9[e]	0.03[f]	0.002[f]	0.00002[f]
Flax [H]	0.3	0.3–0.4	3	6.2 [46][d]	0.2 [0.1][d]	0.03 [1.0][d]	0.0001	<0.001	<0.0003
Flax [I]	0.05	0.04–0.05	3	6.3 [250][d]	0.1 [11][d]	0.3 [1.4][d]	0.002	<0.013	<0.003

[a] Median.
[b] Range.
[c] Number of samples.
[d] Content as analyzed from personal dust samples collected during the full-scale testing.
[e] Content (maximum) as published elsewhere (IARC, 2002).
[f] Personal communication (Kamstrup, 2001).

glass, the OEL of 10^6 fibers/m^3 was used. No OEL for respirable cellulosic fibers is available from the literature. For the purposes of illustration, a concentration of cellulosic WHO fibers was normalized with respect to a concentration of 10^6 fibers/m^3. It is noted that a concentration of cellulosic WHO fibers has to be increased by a factor of 1.3–1.6 (Table 5) for an assessment of exposure to respirable fibers. An OEL of 10 mg/m^3 (non-specific 'total' mineral dust) was used for dust from mineral wool, fiberglass or perlite. In terms of 'total' dust, the following OELs were used for the chemical constituents considered in the study: 2 mg/m^3 for boron, 2 mg/m^3 for aluminum, 0.05 mg/m^3 for lead, 0.005 mg/m^3 for cadmium and 0.5 mg/m^3 for chromium. The Dutch OEL of 200 EU/m^3 (Thorn *et al.*, 2002) was used for inhalable endotoxin. To allow the risk assessment, all the present data on exposure to inhalable dust (Table 3) were converted, per type of insulation material, to 'total' dust by the factors listed in Table 5. A concentration derived in this way was normalized with respect to the OEL and the risk assessments for all the specific contaminants are summarized for the installers in Fig. 6 (insulation of attic spaces) and Fig. 7 (insulation of walls). Compared to the installer's, exposure levels were low for the helpers and for brevity the risk assessment is not given for the helpers.

QUALITY ASSURANCE

The result of the comparison of the PCM and PLM counting method is shown in Table 9. The cumulative distributions of fiber diameters are shown in Fig. 8. Percentiles are given in Table 10. The results of total fiber counts obtained by the PCM and PLM method were comparable (Table 9). However, the PLM method appeared to underestimate the fiber diameter compared with the PCM method. The present PCM respirable fiber counts are low by a factor 1.5 – 2 and the PLM respirable fiber counts by a factor of ~2.5 compared with the IOM results. Due to the lack of suitable specimens for intercomparison with other fiber types, it will be assumed that the relative concentrations for all fiber types as determined by PLM would be the same if the analysis had been by PCM.

DISCUSSION

In the present study, dust sources other than a given type of insulation material were minimized as far as possible. Resuspension of dust from personal clothing has been reported as an important contaminant source for installers of insulation materials (Esmen *et al.*, 1982). Therefore, all workers were dressed in new overalls made of Tyvek, which also ensured that their outermost personal clothing was identical. The laboratory was located in a rural area and the dust concentration in open air was low (0.024 mg/m^3). The concentration of endotoxin in open air was not measured but recent data for a rural area in Denmark were low, ranging from 0.3 to 3.1 EU/m^3 (Nielsen *et al.*, 1997). The concentration of fibers in open air was not measured. However, it appears reasonable to assume the concentration level to be at or below the following concentrations reported (Schneider *et al.*, 1996) for non-occupational exposure by inhalation of fibers in northern Europe:

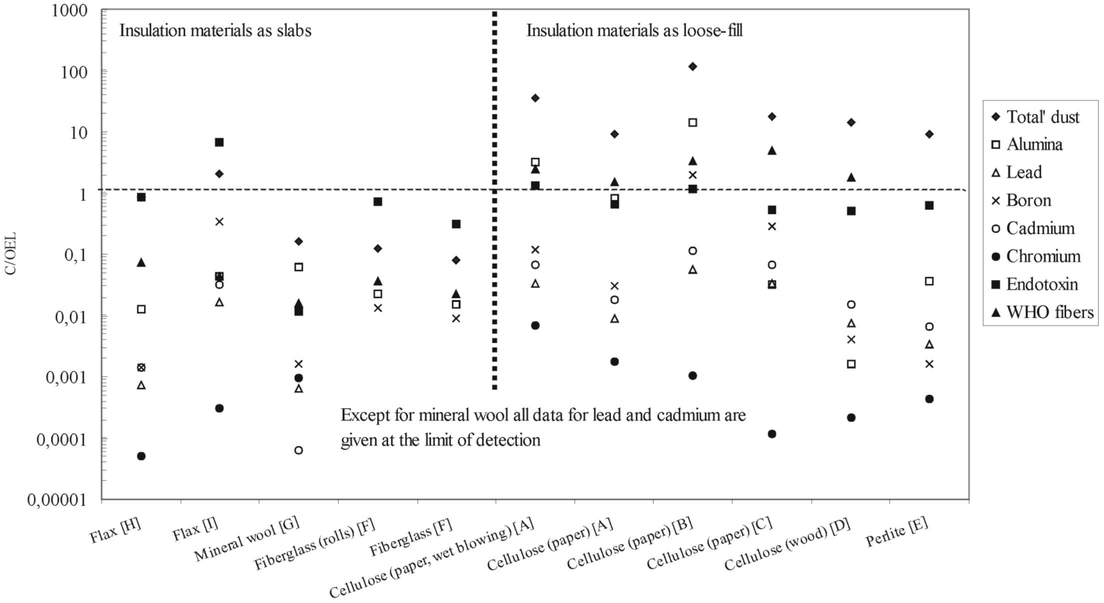

Fig. 6. Exposure by inhalation of dust and WHO fibers. Risk assessment for installers working in attic spaces. For a given contaminant, *C* is the breathing zone concentration and OEL is the equivalent occupational exposure limit. For the purpose of illustration a concentration of cellulosic WHO fibers was normalized with respect to a concentration of 10^6 fibers/m^3, but it has to be emphasized that no OEL is available for cellulose fibers. The type of insulation material (A–I) is specified in Table 1. Note that the exposure to endotoxin includes data from the insulation of walls (see Table 7).

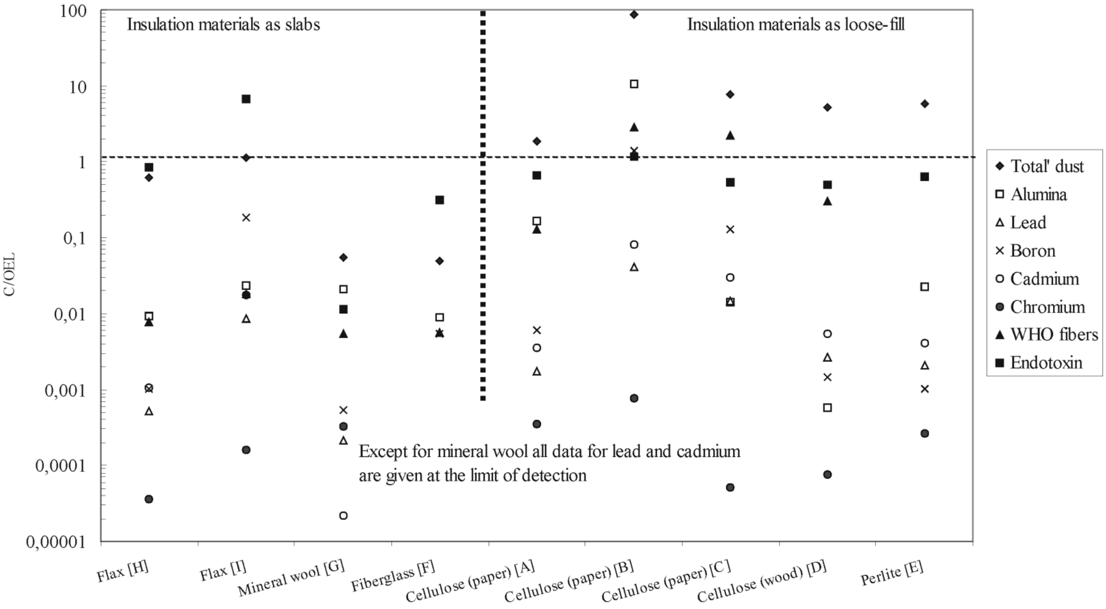

Fig. 7. Exposure by inhalation of dust and WHO fibers. Risk assessment for installers working at cavities of the walls. For a given contaminant, *C* is the breathing zone concentration and OEL is the equivalent occupational exposure limit. For the purpose of illustration a concentration of cellulosic WHO fibers was normalized with respect to a concentration of 10^6 fibers/m^3, but it has to be emphasized that no OEL is available for cellulose fibers. The type of insulation material (A–I) is specified in Table 1. Note that the exposure to endotoxin includes data from the insulation of attic spaces (see Table 7).

9–20 × 10^3 fibers/m^3 (organic fibers), 0.6–4 × 10^3 fibers/m^3 (gypsum fibers) and <1.0 × 10^3 fibers/m^3 (man-made mineral fibers). Except for mineral fibers, it appears reasonable to assume that the background level of air contaminants can be neglected.

Rappaport (1991) has defined homogeneity of

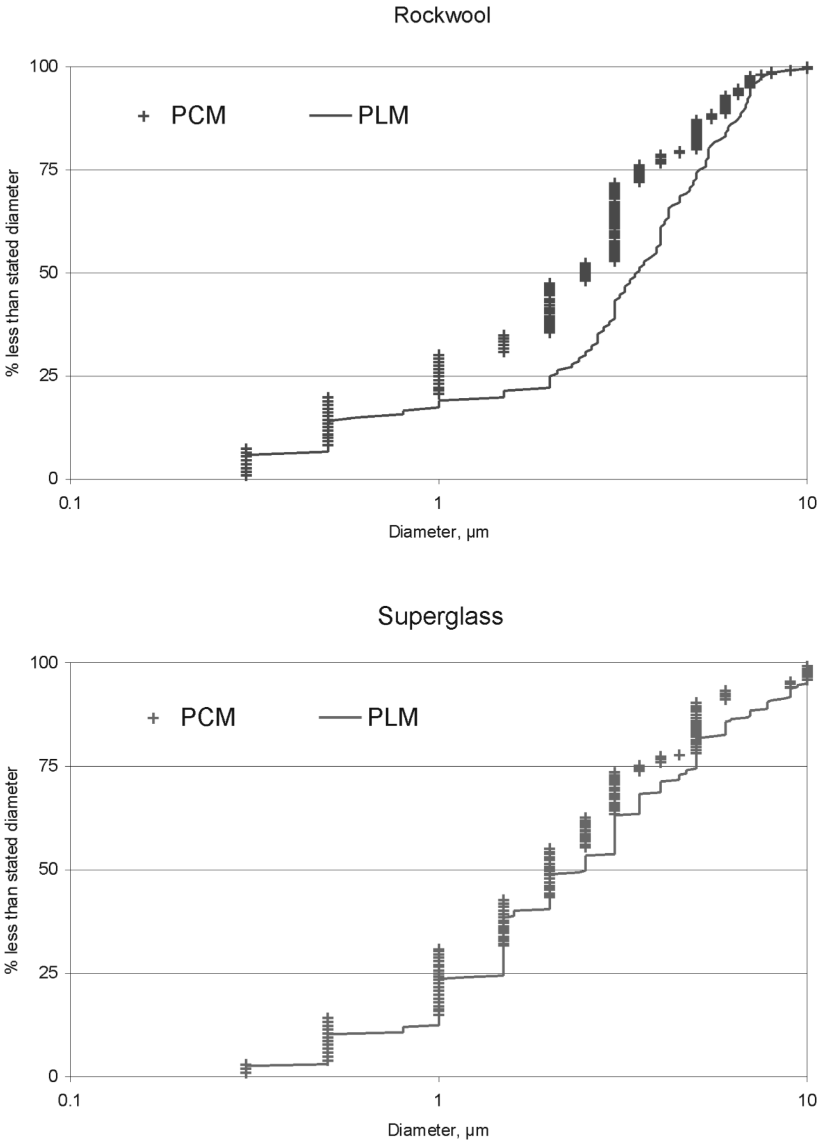

Fig. 8. Cumulative distribution of fiber diameter.

Table 9. Fiber counts on slides formerly in the WHO/EURO reference scheme

Sample	*n*	Endpoints	Weights	Total fibers/mm^2	Respirable fibers/mm^2	% respirable	IOM
Rockwool, PCM	183	113	100.5	60	42	70	64
Rockwool, PLM	138	117.5	119	56	24	43	
Superglass, PCM	160	78.5	95.1	172	136	79	267
Superglass, PLM	225	219	228	175	110	63	

n, number of fibers assessed; endpoints, half sum of endpoints within field; weights, sum of weights (rule G, see text); IOM, estimated respirable fiber density using the PCM method as quoted by IOM.

exposure of a group of workers by the ratio ($R_{0.95}$) between the 97.5th and the 2.5th percentile of the log-normally estimated mean exposure of a group of workers. The exposure group was considered homogeneous if $R_{0.95} < 4$. In real life it is known that it is difficult to create homogeneous exposure groups *a priori* (Kromhout *et al.*, 1993; Rappaport *et al.*, 1993; Mäkinen *et al.*, 2000). Table 3 shows that no more than 50% of the matrix elements met the criterion $R_{0.95} < 4$. It can be assumed that if different

Table 10. Percentiles of fiber diameter as determined by PCM and PLM

Sample	25th percentile		50th percentile	
	PCM	PLM	PCM	PLM
Rockwool	1.0 µm	2.0 µm	2.5 µm	3.5 µm
Superglass	1 µm	1.5 µm	2 µm	2.5 µm

workers had been involved, even fewer matrix elements would fulfil this criterion. For WHO fibers (Table 4) only 30% of the matrix elements fulfilled the criterion. It can be concluded that even under well-controlled conditions such as in the present study it is difficult to create homogeneous exposure groups.

From the literature, some data are available on the exposure by inhalation of dust during the installation of loose-fill, paper-based cellulosic insulation materials. In terms of ‘total’ dust, Mueller (1992) reported a concentration of 920 mg/m^3 for the installation in an attic, while McConnell (1995) reported concentrations ranging from 21 to 35 mg/m^3. For insulation of attic spaces, Dobby *et al.* (2000) reported concentrations of ‘total’ dust ranging from 2.8 to 73 mg/m^3 for the installer and from 0.2 to 46 mg/m^3 for the helper. In terms of inhalable dust, Fuehres and Heidermanns (1993) reported a concentration of 30 mg/m^3 for a simulated insulation of an attic. For the insulation of walls, McConnell (1995) reported a ‘total’ dust concentration of 5.2 mg/m^3, while McCammon and Lee (1991) reported concentrations ranging from 2.2 to 4.6 mg/m^3 for the installer and 13 mg/m^3 for the helper. Fuehres and Heidermanns (1993) performed a simulated insulation of a wall, and in terms of inhalable dust they reported a concentration of 150 or 190 mg/m^3 for dry- and wet-blowing techniques, respectively. For wood-based cellulosic loose-fill materials, Faul *et al.* (2000) reported for the installer an exposure (inhalable dust) ranging from 18 to 130 mg/m^3 for installing the material in an attic and 58 mg/m^3 for the insulation of a wall. For exposure to dust during the installation of cellulosic slab materials, very few data have been published. In terms of inhalable dust, Faul *et al.* (2000) reported a concentration of 13 mg/m^3 for work in an attic space. Three studies have been published on dust measurements during installation of slabs of man-made mineral fibers in buildings (IARC, 2002). They were conducted in Europe in the 1970s and 1980s and showed mean dust concentrations from 2.6 to 36 mg/m^3**.** These results cannot be assumed to represent present-day exposures due to the effects of implementing codes of practice and other exposure-reducing actions. As already mentioned, dust sources other than a given type of insulation material was minimized in the present study. Thus, it is difficult to compare data from field studies with the present measurements (Table 3).

The exposure was positively correlated to dustiness of the materials (Fig. 5) and this supports the usefulness of dustiness testing of insulation materials. For classification of materials in terms of dustiness, Chung and Burdett (1994) suggested five categories: not dusty (<0.01%), slightly dusty (0.01–0.1%), dusty (0.1–1%), very dusty (1–10%) and extremely dusty (>10%). Following this scale, dustiness of the tested materials ranged from not dusty (mineral wool or fiberglass) to extremely dusty (perlite).

Data are sparse on exposure by inhalation to chemicals from fire- or mold-resistant additives in insulation materials. For installing cellulosic loose-fill insulation in an attic, Mueller (1992) reported an exposure of 55 mg/m^3 of boron for the installer, and for a simulated insulation of a wall, Fuehres and Heidermanns (1993) reported an exposure of 15 mg/m^3 of boron for the installer. The present study found much lower exposures (Table 7).

There are some studies on fiber exposure during installation of cellulosic insulation materials in real buildings. In terms of WHO fibers, Mueller (1992) reported the median exposure to range from 3.5 to 9 × 10^6 fibers/m^3 for the installation of loose-fill material in attic spaces. Rather similar median exposures, ranging from 11 to 42 × 10^6 fibers/m^3, were reported by Tiesler and Schnittger (1992) for the installation of loose-fill materials below a floor or in attic spaces. Fuehres and Heidermanns (1993) reported median exposures ranging from 0.5 to 1.0 × 10^6 fibers/m^3 for the installation of loose-fill materials in walls. Recently, Dobby *et al.* (2000) reported median exposures ranging from 0.3 to 1.1 × 10^6 fibers/m^3 during the installation of loose-fill materials in attic spaces. So far, no data appear to have been published on exposure to WHO fibers during the installation of slab materials from flax. Measurements in Europe of breathing zone concentrations of WHO fibers during installation of man-made mineral fiber slabs in buildings showed means ranging from 0.1 to 0.8 × 10^6 fibers/m^3 (IARC, 2002). They were conducted in the 1970s and 1980s and, as previously mentioned, cannot be assumed to represent present-day exposures. Furthermore, at that time no clear distinction was made between mineral fibers originating from the material installed (product fibers) and other sources. Studies from the 1990s and onward in the US and Australia reported mean task length WHO fiber concentrations during installation of man-made mineral wool slabs in buildings of the order 0.1–0.2 × 10^6 fibers/m^3 (IARC, 2002). The results indicate that the results of the present study (Table 4) are at the low end of what can be expected during installation of slabs in real buildings. For reasons already mentioned, it is difficult to compare data from field studies with the present measurements. As mentioned above (Quality Assurance section), the present study used the PLM counting method as an alternative to the WHO method (PCM counting). It has to be noted that such an approach biased the reported fiber concentrations towards low levels. As a rough estimate, the concentration of respirable fibers is biased by a factor of 2.0.

A screening limit value of 6.1 mg/m^3 inhalable dust (Table 6) has been derived from parallel measurements of WHO fiber and inhalable dust exposures. At construction sites, sources other than the insulation material may add airborne dust and so decrease the fibers concentration in the dust. Thus, for practical applications, the proposed screening limit value is conservative.

For inclusion of exposure to cellulose fibers, a reference value for WHO fibers similar to the OEL for man-made mineral fibers was used for illustration only (Figures 6 and 7). Cellulose fibers have not been subjected to the same rigorous toxicity testing that has been applied to man-made mineral fibers (Davis, 1993). Cellulose fibers have been shown to be durable in rat lungs (Muhle *et al.*, 1997), indicating the potential for these fibers to be harmful when inhaled by man. In a recent experiment, rats were exposed to cellulose fibers by intraperitoneal injection (Cullen *et al.*, 2002). The fibers caused harmful effects, including tumors that, however, were mainly sarcomas, which are not normally seen with mineral fibers. The authors concluded that the implications for the ability of cellulose fibers to cause pulmonary carcinomas following inhalation remains unknown and that long-term inhalation studies are recommended. For installers in attic spaces, the assessment of exposure to dust and WHO fibers indicated low risk from the installation of slab materials from mineral wool or fiberglass. Slab materials from flax (supplier I) caused high risk of exposure to endotoxin. The risk of exposure to dust from loose-fill materials was high for installers in attic spaces and for some of the materials risk of exposure was high for elements (boron and aluminum) from fire- or mold-resistant additives. In general, exposure to cellulosic WHO fibers was high (well above the OEL for man-made mineral fibers), but little is known about the health effects and a risk assessment is not possible. For the insulation of walls, the risk of installers' exposure to dust and fibers was low for the slab materials, while a high risk was observed for loose-fill materials. The observed high risk of exposure to dust and fibers from loose-fill materials calls for protective measures such as dust respirators. For helpers, exposure to dust and fibers was low compared to the installers.

CONCLUSION

For installers in attic spaces, risk of exposure was low by inhalation of dust and WHO fibers from slab materials of mineral wool or fiberglass. Slab materials from flax may cause high risk of exposure to endotoxin. The risk of exposure to dust from loose-fill materials was high for installers in attic spaces and for some of the materials risk of exposure was high for elements (boron and aluminum) from fire- or mold-resistant additives. Exposure to cellulosic WHO fibers was high, but little is known about the health effects and a risk assessment is not possible. For the insulation of walls, the risk of installers' exposure to dust and fibers was low for the slab materials, while a high risk was observed for loose-fill materials. Exposure to WHO fibers was positively correlated to the dust exposure. A dust level of 6.1 mg/m^3 was shown to be useful as proxy for screening exposure to WHO fibers in excess of 10^6 fibers/m^3. Slabs of insulation material from mineral wool or fiberglass were tested not dusty, while cellulosic loose-fill materials were tested very dusty and perlite proved extremely dusty.

Acknowledgements—This study was sponsored by the Danish Energy Authority (grant no. 75664/99-0058).

REFERENCES

Arbejdstilsynet. (2000) Grænseværdier for stoffer og materialer. At-vejledning C.0.1. København: Arbejdstilsynet.

BOHS. (1985) Dustiness estimation tests for dry materiales. In British Occupational Hygiene Society technical guide no. 4. Northwood: Science Reviews Ltd.

Breum NO. (1999) The rotating drum dustiness tester: variability in dustiness in relation to sample mass, testing time, and surface adhesion. Ann Occup Hyg; 43: 557–66.

Breum NO, Nielsen EM, Nielsen BH. (1996) Bioaerosol exposure in collecting garden waste, recyclable materials and waste for incineration. Ann Agric Environ Med; 3: 27–32.

Breum NO, Schneider T, Flyvholm MA, Jørgensen O, Valdbjørn Rasmussen T, Skibstrup Eriksen S (2002) Luftforureninger ved anvendelse af alternative isoleringsmaterialer. AMI Rapport 57. Copenhagen: National Institute of Occupational Health.

Buick JB, Lowry RC, Magee TRA. (1994) Isolation, enumeration, and identification of gram negative bacteria from flax dust with reference to endotoxin concentration. Am Ind Hyg Assoc J; 55: 59–61.

Chung KY, Burdett GJ. (1994) Dustiness testing and moving towards a biologically relevant dustiness index. Ann Occup Hyg; 38: 945–9.

Cullen RT, Miller BG, Jones AD, Davis JMG. (2002) Toxicity of cellulose fibres. Ann Occup Hyg; 46(suppl. 1): 81–4.

Davis JMG. (1993) The need for standardised testing procedures for all products capable of liberating respirable fibres: the example of materials based on cellulose. Br J Ind Med; 50: 187–90.

Dobby JM, Kedrowski D, Shinn NJ. (2000) Employee exposure monitoring—cellulose building insulation installation for North American Insulation Manufacturers Association. Chicago, IL: Carnow, Conibear & Assoc. Ltd.

Dybro Juhl H, Husemoen T, Lindqvist H, Nordh I, Trappmann J. (1998) Standard full-scale chamber test conditions for examination of mineral wool products. Gefahrstoffe-Reinhaltung der Luft; 58: 349–52.

Esmen NA, Sheehan MJ, Corn M *et al*. (1982) Exposure of employees to manmade vitreous fibers: Installation of insulation materials. Environ Res; 28: 386–98.

Faul L, Fuehres M, Gorzelitz G, Reichert F. (2000) Staubbelastungen beim Umgang mit naturlichen organischen Faserdammstoffen. Staub-Reinhaltung der Luft; 60: 39–45.

Fuehres M, Heidermanns G. (1993) Fasermessungen bei der Verwendung von Zellulose-Fasern. VDI Berichte; 1075: 345–56.

Gonda J, AbdElKhalik AF. (1985) On the calculation of aerodynamic diameters of fibres. Aerosol Sci Tech; 4: 233–8.

IARC. (2002) IARC monographs on the evaluation of carcinogenic risks to humans: man made vitreous fibers. Vol. 81. Lyon: International Agency for Research on Cancer.

Kamstrup O. (2001) Personal communication from Rockwool International A/S, Denmark.

Kenny LC, Aitken R, Chalmers C *et al*. (1997) A collaborative European study of personal inhalable aerosol sampler performance. Ann Occup Hyg; 41: 135–53.

Kromhout H, Symanski E, Rappaport SM. (1993) A comprehensive evaluation of within- and between-worker components of occupational exposure to chemical agents. Ann Occup Hyg; 37: 253–70.

Mäkinen M, Kangas J, Kalliokoski P. (2000) Applicability of homogeneous exposure groups for exposure assessment in the chemical industry. Int Arch Occup Environ Health; 73: 471–8.

McCammon C, Lee S. (1991) Asbestos exposure during low-income housing weatherization. Appl Occup Environ Hyg; 6: 347–8.

McConnell EE. (1995) Summary of data for chemical selection: cellulose insulation. Prepared for NTP by Technical Resources International Inc under contract no. N01-CP-56019.

Milton DK, Walters MD, Hammond K, Evans JS. (1996) Worker exposure to endotoxin, phenolic compounds, and formaldehyde in a fiberglass insulation manufacturing plant. Am Ind Hyg Assoc J; 57: 889–96.

Mueller CJ. (1992) Industrial hygiene assessment of airborne cellulose insulation at Cliff Place by Single Constructions. Clayton project no. 39049.00. Pleasanton, CA: Clayton Environmental Consultants.

Muhle H, Ernst H, Bellmann B. (1997) Investigation of the durability of cellulose fibres in rat lungs. In Cherry N, Ogden T, editors. Inhaled particles VIII, proceedings of an international symposium on inhaled particles, Cambridge, 1996. Ann Occup Hyg; 41(suppl. 1): 184–8.

Nielsen EM, Breum NO, Nielsen BH, Würtz H, Poulsen OM, Midtgård U. (1997) Bioaerosol exposure in waste collection: comparative study on the significance of collection equipment, type of waste and seasonal variation. Ann Occup Hyg; 41: 325–44.

Rappaport SM. (1991) Assessment of long-term exposures to toxic substances in air. Ann Occup Hyg; 35: 61–121.

Rappaport SM, Kromhout H, Symanski E. (1993) Variation of exposure between workers in homogeneous exposure groups. Am Ind Hyg Assoc J; 54: 654–62.

Schneider T. (1979) The influence of counting rules on the number and on the size distribution of fibers. Ann Occup Hyg; 21: 341–50.

Schneider T, Burdett G, Martinon L *et al*. (1996) Ubiquitous fiber exposure in selected sampling sites in Europe. Scand J Work Environ Health; 22: 274–84.

Thorn J, Beijer L, Jonsson T, Rylander R. (2002) Measurement strategies for the determination of airborne bacterial endotoxin in sewage treatment plants. Ann Occup Hyg; 46: 549–54.

Tiesler H, Schnittger J. (1992) Untersuchungen zur Belastung durch faserförmige Stäube bei der Verarbeitung von Cellulose-Dämmstoffen. Zbl Arbeitsmed; 42: 278–85.

WHO. (1996) Determination of airborne fibre number concentrations. A recommended method, by phase contrast optical microscopy (membrane filter method). Geneva: World Health Organization.