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Corrections

See [1985;11\(6\):500](#) for a correction.

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Man-made mineral fiber size fractions and their interrelation

by Thomas Schneider, MSc,¹ Jørgen Skotte, MSc,¹ Povl Nissen²

SCHNEIDER T, SKOTTE J, NISSEN P. Man-made mineral fiber size fractions and their interrelation. *Scand J Work Environ Health* 11 (1985) 117–122. The fiber fractions RFOM (respirable fibers, determined by optical microscopy), SF (Stanton fibers), PF (Pott fibers), and FLOM (total length of optically visible, respirable fibers) and their ratios have been (i) determined experimentally in fiber sizes obtained by scanning electron microscopy of air samples of man-made mineral fibers and (ii) calculated theoretically for a range of fiber size distributions, assumed to be bivariate log-normal. For realistic values of fiber size parameters, RFOM and even FLOM are good predictors of Stanton and Pott fibers, the better the more-detailed the size information available is. The results point towards a possibility of estimating past exposure to Stanton or Pott fiber fractions of airborne man-made mineral fibers, even though only RFOM were determined.

Key terms: accumulated length, fiber size distribution, past exposure, Pott fiber, respirable fiber, Stanton fiber.

The routine method for determining the concentration of airborne man-made mineral fibers (MMMMF) is based on phase contrast optical microscopy. By definition, only fibers having a diameter (D) of $\leq 3 \mu\text{m}$, a length (L) of $\geq 5 \mu\text{m}$, and an aspect ratio (AR) of $\text{AR} = \text{L}/\text{D} \geq 3$ are counted. Due to the reduction in the contrast of thin fibers, as seen in an optical microscope, only fibers having $\text{D} > 0.15\text{--}0.2 \mu\text{m}$ are visible. This lower limit is dependent on the optical parameters (2).

Stanton et al (5) analyzed the probability of tumor production in experimental animals after pleural implantation of mineral fibers in terms of fiber number in various size categories. It was found that the probability of pleural sarcoma correlated best with fibers that had a diameter of $\leq 0.25 \mu\text{m}$ and a length of $> 8 \mu\text{m}$. A relatively high correlation was also found with fibers in other categories having a diameter of $\leq 1.5 \mu\text{m}$ and a length of $> 4 \mu\text{m}$. These findings have led to the introduction of Stanton fibers, ie, fibers having a diameter of $\leq 1.5 \mu\text{m}$ and a length of $\geq 8 \mu\text{m}$.

To appreciate the fact that the fiber carcinogenicity following implantation or injection is size dependent, Pott (1) developed a hypothesis according to which there exists a gradual transition from the ineffective fiber length or diameter to the fiber length or diameter which possesses maximum fiber carcinogenicity. S-shaped curves having 50 % values for diameter at $0.5 \mu\text{m}$ and for length at $7 \mu\text{m}$ were hy-

pothesized for length- and diameter-dependent carcinogenicity. The product of the two curves is then the carcinogenicity factor or weighting to be used. The sum of these weights, calculated for each fiber in a dust sample, can then be termed the number of Pott fibers in that sample.

Within certain length limits, the Pott hypothesis is quantitatively saying that two short fibers are as risky as one long one. This proposal has led to the suggestion that the total fiber length within a certain diameter range could be a useful predictor of risk (4, 7). It has been pointed out that the total fiber length is very easy to determine by microscopy (7). It can be done by merely counting all fibers crossing the center point of an eyepiece graticule (intercept method).

The purpose of most measurements of airborne fibers is to assess a health risk. For this purpose, one can evaluate the fibers present in a sample differently to obtain an appropriate risk estimator.

The following risk estimators will be used:

RFOM: the number of fibers in a sample having $0.2 \leq \text{D} \leq 3 \mu\text{m}$, $\text{L} \geq 5 \mu\text{m}$, and $\text{L}/\text{D} \geq 3$,

SF: the number of fibers in a sample having $\text{D} \leq 1.5 \mu\text{m}$ and $\text{L} \geq 8 \mu\text{m}$,

PF: all fibers p_i , where p_i is the carcinogenicity factor given by Pott (1) [in terms of D and L the following expression was used: $p_i = 1/(1 + \exp((\ln D_i + 0.693)/0.324))(1 + \exp(-(1/\text{L}_i - 1.946)/0.324))$], and

FLOM: $\Sigma(\text{L}_i | 0.2 \leq \text{D} \leq 3)$, ie, the total length in microns of all fibers having $0.2 \leq \text{D} \leq 3 \mu\text{m}$. ($\text{L} < 5 \mu\text{m}$ and $\text{L}/\text{D} < 3$ is included).

Stanton et al (5) pointed out the difficulty in the statistical analysis of the significance of the various

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Table 1. Parameters of the size distributions, calculated from the pooled fiber size data for each site.

Site	Number of samples	Diameter		Length		τ_{DL}^a
		Geometric mean (μm)	Geometric standard deviation	Geometric mean (μm)	Geometric standard deviation	
Rock wool, plant A	6	0.95	3.1	13	3.4	0.60
Rock wool, plant B	38	0.99	3.3	14	3.6	0.66
Rock wool, special fibers C 1	6	1.46	2.8	27	3.3	0.54
Rock wool, conventional fibers C 2	28	1.73	2.4	22	3.1	0.48
Use of rock wool	21	1.20	2.7	22	4.0	0.67
Use of glass wool	8	0.75	2.8	16	3.5	0.65

^a τ_{DL} = correlation between $\ln D$ and $\ln L$.

Figure 1. Geometric mean (closed circles) and geometric standard deviation of the ratios calculated for each filter sample. From top: Sites A, B, C1, C2, use of rock wool, use of glass wool. The open circles are theoretical values; see the text. Also shown is a postulated interlaboratory (interlab) variation. (SF = Stanton fibers, PF = Pott fibers, RFOM = optical respirable fibers, FLOM = total length of optical respirable fibers)

Figure 2. Plot of diameter and length of individual fibers from a man-made mineral fiber (MMMF) population (log-log scale).

size categories in relation to tumor production. The difficulty arises from the fact that the number of fibers in adjacent size categories are highly correlated, and accordingly the various risk estimators are correlated. It is therefore relevant to investigate the relation between the various risk estimators.

Experimental results

In order to determine these relations, we have analyzed fiber size data from three manufacturing plants (all rock wool) and from the user industry (one rock wool and one glass wool). The fiber sizes had been determined by scanning electron microscopy of air samples. Summary statistics are given in table 1.

For each filter sample RFOM, SF, PF, and FLOM were calculated. The geometric mean and geometric standard deviation of the ratios SF:RFOM, PF:RFOM, RFOM:FLOM, SF:FLOM, and PF:FLOM were then calculated. The results are shown in figure 1. So that the variability of the single sample ratios can be put into perspective, a postulated interlaboratory variation in fiber counts on individual samples is also shown in figure 1.

Theoretical results

The previous calculations were based on rather uniform size distributions; see table 1. In order to explore the range of the ratios when the size distributions are allowed to vary considerably, we made some theoretical calculations.

To facilitate a systematic approach, some assumptions about the size distributions have to be made. If $f_D(d)$ and $f_L(l)$ denote the probability density functions of D and of L , then for the joint probability density function $f(d, l)$ one has in general that

$$f(d, l) \neq f_D(d) f_L(l),$$

since d and l are correlated. This is apparent from figure 2. Figure 2 suggests also that $(\ln D, \ln L)$ follow a bivariate normal distribution, ie, (D, L) is bivariate log-normal.

The use of the bivariate log-normal distribution to describe size data on man-made mineral fibers has been introduced by Schneider & Holst (3), to the report of whom the reader is referred for details. Using a short-hand notation, one can express that (D, L) is bivariate log-normal in the following way:

$$(\ln D, \ln L) \in N(\mu_D, \mu_L, \beta_D^2, \beta_L^2, \tau_{DL}).$$

The distribution is seen to be completely characterized by five parameters. Their meaning is apparent from the following:

$$\ln D \in N(\mu_D, \beta_D^2),$$

saying that the marginal distribution of D is log-normal with parameters μ_D and β_D ie,

$$\text{median diameter CMD} = \exp(\mu_D)$$

$$\text{geometric standard deviation GSD}(D) = \exp(\beta_D)$$

and similarly for the marginal distribution of L :

$$\text{median length CML} = \exp(\mu_L)$$

$$\text{geometric standard deviation GSD}(L) = \exp(\beta_L)$$

τ_{DL} is the correlation between $\ln D$ and $\ln L$ (not between D and L). The explicit expression is

$$f(d, l) = \frac{1}{2\pi\beta_D\beta_L(1-\tau_{DL}^2)^{1/2}} \frac{1}{dl} \exp \left[-\frac{A^2 + B^2 - 2\tau_{DL}AB}{2(1-\tau_{DL}^2)} \right],$$

where $A = (\ln d - \mu_D)/\beta_D$ and $B = (\ln l - \mu_L)/\beta_L$.

The risk estimators are thus easily obtained with the use of numerical integration of the following expressions:

$$\text{RFOM} = \int_{x=0.2}^3 \int_{y=5}^{\infty} f(x, y) dx dy.$$

The stepwise contributions in the numerical integration were set to zero if $y/x < 3$.

$$\text{SF} = \int_{x=0}^{1.5} \int_{y=8}^{\infty} f(x, y) dx dy.$$

Notice that y/x always exceeds 3

$$\text{PF} = \int_{x=0}^{\infty} \int_{y=0}^{\infty} p(x, y) f(x, y) dx dy.$$

FLOM is more easily calculated because the accumulated fiber length distribution is also log-normal, having mean $= \mu_D + \mu_L \tau_{DL}$ and variance $= \beta_D^2$; see the report of Schneider & Holst (3). Thus

$$\text{FLOM} = \frac{1}{2\pi \exp(\beta_D^2)} \int_{x=0.2}^3 \frac{1}{x} \exp \left(-\frac{(\ln x - \mu_D - \beta_D \beta_L \tau_{DL})^2}{2\beta_D^2} \right) dx.$$

The round figures 30 and 100 have been chosen for the ratios 30 SF:FLOM and 100 PF:FLOM in order to make the ratios more comparable.

The numerical integrations have been carried out, and the ratios calculated for

$$\text{CMD} = \exp(\mu_D) = 0.354; 0.5; 0.707; 1.0; 1.41; 2,$$

$$\text{CML} = \exp(\mu_L) = 2.5; 5; 10; 20; 40,$$

$$\text{for GSD}(D), \text{GSD}(L) = 1.7, 2.2; 2, 3; 3, 4,$$

$$\text{and for the correlation } \tau_{DL} = 0; 0.3; 0.6; 0.9.$$

Figure 3. Theoretical calculations for Stanton (SF) and Pott (PF) fibers relative to optical respirable fibers (RFOM).

The values for the 30 grid points were interpolated and the iso plots constructed with the use of the GEOPAK (6) interpolation, contouring, and plotting program. The results are shown in figures 3 and 4. The results are estimated to be accurate to about $\pm 5\%$, except for some interpolation artifacts due to some extreme values in some grid points near the edge. Individual values were also calculated with the use of the estimated parameters in table 1 and shown in figure 1 for comparison.

Discussion

Figure 1 shows that there are deviations between the experimental and theoretical results, as well as within each group of experimental results.

Part of the variation in the experimental results are due to the fiber number per given filter area, assumed to be Poisson distributed. However, PF and FLOM are determined as weighted sums, which make a calculation of the effect of the Poisson contribution difficult, and no statistical evaluation of this aspect has been attempted.

The theoretical results in figure 1 have been calculated based on an assumed log-normal distribution and based on estimated parameters. The agreement between the theoretical and experimental results was however, satisfactory. It is concluded that the model is quite robust and that the theoretical results are reliable.

For high correlations ($\tau_{DL} = 0.9$) or small geometric standard deviations [$GSD(D) = 1.7$ and $GSD(L) = 2.2$] the ratios shown in figure 3 cover a

Figure 4. Theoretical calculations for 30 Stanton (SF) and 100 Pott (PF) fibers, relative to total length of optical respirable fibers (FLOM).

considerable range. However, such values of the size parameters are unlikely to occur in practice (table 1). It is interesting to note what happens if the values of CMD and CML are further restricted to aspect ratios between, eg, 5 and 20. Then, even without any knowledge of CMD or CML, the ratio SF:RFOM would vary with a factor of less than about two. This value is of the same magnitude as systematic differences in counting results obtained by different laboratories. RFOM is thus a good predictor of SF. If some information is available on the actual fiber sizes, SF can be estimated more accurately.

Theoretical considerations (4) show that it is possible to estimate fiber size data for historical fiber exposure, based on a size analysis of historical bulk samples. It seems therefore possible to estimate, with quite some certainty, historical exposure to Stanton

fibers in mineral wool manufacturing plants, even though no or only optical microscopy fiber counting results exist back in time.

It is remarkable that even Pott fibers can, in theory, be predicted quite well from optical microscopy data in combination with only rough estimates of fiber size parameters. Detailed knowledge improves the prediction considerably; see also figure 1.

Figure 4 shows that, compared to the ratios in figure 3, the ratios 30 SF:FLOM respectively 100 PF:FLOM vary within the same limits. However, the restriction to a certain range of aspect ratio does not in general reduce this variation to the same degree.

Nevertheless, if there is some knowledge of fiber size, even FLOM can be a very good predictor of SF and even of PF; see also figure 1. The determination of the total length of optically visible respirable fibers

appears to be an alternative to conventional fiber counting.

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