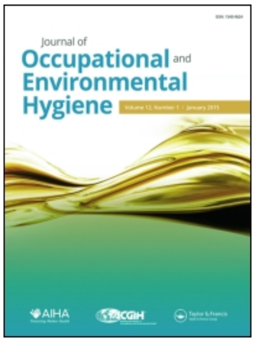

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Determinants of Airborne Fiber Size in the Glass Fiber Production Industry

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Size distributions of airborne fiber exposures should be characterized for studies of respiratory disease because size determines the region of the lung where a fiber will deposit and its ability to produce toxic effects in cells. Yet fiber size is not measured precisely with standard air sampling methods. Specific fiber dimensions hypothesized to have biologic activity have been proposed, but these have not been evaluated in epidemiologic studies because there has not been a way to account for fiber size in historical air monitoring data. In this study, methods were developed to predict fibrous aerosol size fractions generated during glass wool fiber production using regression models and factors related to bulk fiber products and processing. A set of air samples representing a range of products and process applications was collected in eight fiber glass production facilities. The samples were analyzed more intensively than standard methods require. For each air sample, total fiber size distributions were measured using electron microscopy and two proportions were then calculated: (1) fibers meeting the size criteria of the standard NIOSH Method 7400 B rules method (p_B), and (2) fibers meeting the size criteria for a biologically based exposure index, the hypothetically active fiber (HAF1) index (p_{H1}). The fiber size proportions were used as dependent variables in regression models with production process factors. It was found that two factors, the nominal diameter of the bulk fiber product and whether oil was applied to it, determine more than 80% of the variability in the proportions (for the p_B model, $R^2 = 0.86$; for the p_{H1} model, $R^2 = 0.82$). Using these two predicted proportions, it is possible to estimate the concentration of fibers in the biologically based HAF1 size fraction from a standard fiber concentration measurement. The models developed here can be used to size-adjust historical fiber concentration measurements for use in epidemiologic studies of respiratory disease.

Keywords exposure assessment, exposure modeling, fiber size distributions man-made mineral fibers, man-made vitreous fibers, synthetic vitreous fibers

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The man-made vitreous fiber (MMVF) production industry makes a variety of home and commercial building insulation products. The size of fibers in the bulk material used for each product can vary by orders of magnitude, depending on the product specifications. Airborne fiber size distributions (diameter and length) generated during the processing of bulk materials also can vary considerably.[1–7] Airborne fiber size, as well as concentration, should be characterized for studies of respiratory disease because size determines the region of the lung where a fiber is likely to deposit[6] and its ability to produce toxic effects in cells.[8]

While size-selective sampling methods are well developed for measuring the concentration of spherically shaped particles in certain size fractions, fiber size is not measured directly with the most commonly used standard air sampling methods. The standard method for measuring airborne fiber exposure in U.S. workplaces has been the NIOSH Method 7400 with A or B rules.[9] It uses phase contrast optical microscopy (PCOM) for counting the fibers deposited on an air sampling filter. A similar method has been used in Europe. For reasons based primarily on the limitations of PCOM technology, these methods do not count all sizes of fibers collected on an air sampling filter but rather some fraction in a very broad size range.[10] It has been proposed that these standard fiber methods may not measure the fibers having the most biologically active dimensions, and several researchers, including Stanton et al.,[11–13] Pott et al.,[14,15] Lippmann,[16,17] and Quinn et al.,[4,6,7,18] have drawn on toxicologic research to propose specific size ranges that represent hypotheses about the biological activity of fibers related to disease in humans. Each of these indices has a biologically plausible rationale, yet they propose different fiber dimensions.[7] It has not been possible to evaluate these different indices in an epidemiologic study because there has been no way to adjust historical fiber air monitoring data obtained using the standard methods to the newly proposed biologically active fiber indices.

To estimate airborne fiber size when it is not measured directly, we hypothesized that it could be predicted using factors related to the bulk fiber products and their production processes. We then developed an approach to use the fiber size estimates to size-adjust historical fiber concentration measurements. This work was conducted as part of an exposure assessment for an epidemiologic study of respiratory disease and work in the U.S. MMVF production industry.[19–22] Specific objectives were to (1) test the hypothesis that fiber size fractions can be predicted using multiple linear regression models and manufacturing process and product factors for which historical information is available, and (2) use the fiber size fractions to adjust a standard fiber concentration measurement to a biologically based concentration.

BACKGROUND

Description of the Glass Fiber Production Process

This study evaluated glass wool fiber, one of the most common types of MMVF. The type of glass was borosilicate, the glass used in major glass fiber products. MMVF products are made with different nominal diameters depending on their final application. Nominal diameter is a MMVF industry standard measure that represents the average diameter of the bulk fiber product; it is not intended to represent airborne fiber size distributions. In the United States, nominal diameter is determined by measuring the amount of resistance a piece of bulk fiber product has to a puff of air blown through it. A variety of common home and commercial insulation products are made from a moderate- to coarse-sized fiber (nominal diameters approximately 4–12 μm), while some specialty fiber products and blowing wool are made of smaller diameter fibers (nominal diameters approximately 2–4 μm). Some specialty products, such as filtration media, require very fine fibers called microfibers (nominal diameters approximately less than 2 μm).

Glass wool fibers are formed in a process called fiberizing that uses mechanical spinners or flame and forced air (two types of "fiberizers") to blow fibers from a stream of molten glass into the air of a chamber. Oil and/or binder may be sprayed on the fibers as they are formed in midair, depending on the final product specifications. The airborne fibers are then collected on a conveyor belt where they form a mat. If binder was applied, the mat is conveyed through a drying oven where it is cured. Some mats are covered on one or both sides with a sheet of paper or foil, called a facing. The mats are then conveyed to a finishing area where they are cut into batts, rolls, or more specialized shapes. Handling processes often include manipulation of the fiber mats, such as stacking, folding, rolling, bagging, and baling. Some final fiber products like pipe insulation and roofing board require the application of more intense mechanical energy, such as sawing, grinding, and chopping. The MMVF production process is described more fully elsewhere.[21,22]

Previous Investigations of Airborne MMVF Size Distributions

The experimental work of Cherrie et al.[23] and Krantz et al.,[3] as well as several field studies,[1,5,24] provided evidence that the geometric mean diameter (GMD) of airborne fibers decreases with decreasing nominal diameter of the product being handled. In addition, the results of Krantz[24] suggest that the use of oil and/or binder increases the GMD of airborne fibers. Schneider et al.[2] developed a theoretical approach to predict an airborne fiber size distribution using the length-weighted diameter of a bulk fiber product and the processes applied to it. Predictive models of airborne fiber size using product and process factors and actual airborne MMVF diameter and length distribution measurements have not been developed.

Methods for Quantifying Fiber Size Distributions and Indices of Exposure

The Bivariate Lognormal Distribution

If the fibers in a sample of air were tallied according to their dimensions, the result would be the distribution of the number of fibers by their diameters and lengths. Schneider and Holst[25] and Cheng[26] have proposed that such distributions are lognormal and thus can be described by the probability density function for a bivariate lognormal distribution. Bivariate lognormal distributions can be summarized completely by five parameters: the geometric mean diameter GM(D); geometric standard deviation of the diameter GSD(D); geometric mean length GM(L); geometric standard deviation of the length GSD(L); and the correlation of the ln(length) and ln(diameter), τ(DL).

Schneider et al.[27] proposed summarizing fiber size distributions by calculating the five parameters for the fibers counted from an air sample. To obtain the portions of the total fiber size distributions that correspond to those measured by the standard methods and biologically based indices, they proposed integrating the bivariate lognormal distribution within given diameter and length limits. While conceptually useful, this method has practical limitations for use in an epidemiologic exposure assessment because it is complicated to manipulate five parameters calculated from many air samples.

Univariate Proportions

Quinn and colleagues,[4,7,18] proposed a simpler approach that was developed by considering the portion of fibers meeting certain size criteria as a proportion of the total fiber size distribution:

$$p_i = n_i/n_t \quad \textbf{(1)}$$

where

p_i = the proportion of fibers having the diameters and lengths of interest in an air sample
n_i = number of fibers counted having the diameters and lengths of interest in an air sample
n_t = total number of fibers counted in an air sample

The quantity used to summarize fiber diameter and length is then a univariate proportion that can be determined readily for a given air sample. Using a proportion of the total fiber size distribution as the summary measure of the fiber dimensions specified by a standard fiber method or by a biologically based index has advantages over using the five parameters of the bivariate lognormal distribution.

The first is that a proportion is a single measure distributed according to a binomial distribution with a well-described variance, that is, $p(1-p)/n$ where p is the proportion of fibers having the lengths and diameters of interest, here called p_i; n is the total number of fibers counted from each air sample, here called n_t. Second, for large sample sizes (np greater than or equal to 20), the binomial distribution approximates the normal distribution. A univariate measure that is normally distributed with a well-described variance can be used readily as a dependent variable in a general linear model, so that the exposure setting characteristics that affect the p_i can be determined analytically. Finally, a proportion of a total fiber size distribution is not dependent on any particular underlying distribution (the lognormal, for example).

In this study, proportions of fibers meeting the size criteria for two fiber indices were calculated out of the total number of fibers (see below). The proportion of fibers meeting the standard NIOSH Method 7400 B rules, p_B, represented fibers with diameters between 0.25 μm and 3 μm and lengths greater than 5 μm. The proportion of fibers meeting the size criteria for a biologically based fiber index, p_{H1}, called the hypothetically active fiber index, represented fibers having diameters less than 6 μm and lengths approximately greater than 5 μm. The number 1 is added to the HAF notation to indicate that many alternative indices could be constructed using this approach with different criteria about fiber size and toxicity.[18] A description of these indices is given elsewhere.[4,6,7,18]

METHODS

Selection of the Product and Process Factors

Manufacturing process and product factors hypothesized to be determinants of airborne fiber size distributions were identified by (1) conducting walkthrough evaluation surveys of 19 of the oldest and largest MMVF production facilities in the United States, (2) reviews of current and historical process engineering records from these facilities, and (3) a literature review. Only factors for which information could be obtained from historical records of MMVF production facilities were considered because of the interest in using them in models for retrospective exposure assessment. Seven such factors were identified: nominal diameter of the bulk fiber product, use of oil, use of binder, the distance from the fiber generating source defined as near (<5 ft) or far (>15 ft) field, intensity of handling the MMVF product, the type of fiberizer used to form the fibers, and the presence or absence of a facing on the finished product (Tables I and II).

In models to predict fiber size proportions, *nominal diameter* was treated as a continuous variable (mean 3.9 μm, range 0.7 to 6.2 μm, Table I). Typical nominal diameter classifications used in the industry are (1) microfibers (approximately less than 2 μm), which include specialty insulation products and filtration media; (2) fine fibers (approximately 2–4 μm), including specialty products and some types of blowing wool for home insulation; and (3) medium fibers (approximately 4–7 μm), including home and commercial insulation products in the form of batts and pipe insulation. While nominal diameter was included in the regression models as a continuous variable, the mean nominal diameter for each of these three classifications was used to calculate the predicted fiber size proportions (summarized in Table V). It was hypothesized that the HAF1 and NIOSH Method 7400 B rules proportions would increase as nominal diameter increases because both include relatively large diameter fibers.

TABLE I. Continuous Product and Process Factors

Product/Process Factor	N	Mean	SD	Range
Nominal diameter (μm)[A]	60	3.9 μm	1.8	0.7–6.2 μm
Oil[B]	60	1.5%	3.4	0–10.0%
Binder[B]	60	6.3%	4.5	0–13.8%

[A]Nominal diameter was used as a continuous variable in the fiber size proportion models. However, in presenting the results of these models (Table V), the mean nominal diameter for each of three typical industry classifications was used. These are (1) microfiber, typical range 0–2 μm, mean in these data 0.88 μm (SD = 0.19); (2) fine fiber, typical range >2–4 μm, mean in these data 2.88 (SD = 0.55); (3) medium fiber, typical range >4–7, mean in these data 5.02 (SD = 0.72).
[B]Percent by weight of the total bulk fiber product. Oil and binder were measured as continuous variables but treated as categorical variables (any vs. none) in the fiber size proportion models (see text).

TABLE II. Categorical Product and Process Factors

Process/Product Factor	N	Total Air Samples (%)
Field	60	
Near (<5 ft)	49	82
Far (>15 ft)	11	18
Handling	60	
Low handling (forming)	9	15
Moderate mechanical energy input (rolling, stacking, folding)	34	57
High mechanical energy input (sawing, grinding, chopping)	17	28
Fiberizer type	60	
Rotary spinner	36	60
Flame attenuation	24	40
Facing	60	
All faced	18	30
Mixed faced	7	12
None faced	35	58

Oil may be applied to the surface of the fibers during forming to reduce airborne dust. In the industry, oil is measured as a percent by weight of the total bulk fiber product. The oil variable was grouped into two levels, "with oil" and "without oil" (Table I). Most products with oil contained less than 2% oil by weight (mean 2.4%), while a few contained as much as 10%. Krantz et al.[3] applied mechanical energy to bulk fiber product with and without oil in an exposure chamber. They found that the use of oil reduced the airborne fiber concentration but increased the geometric mean diameter (GM(D)) of the airborne fibers. Based on the work of Krantz and co-workers,[3] we hypothesized that oil would increase the GM(D) of the airborne MMVF.

Binder may be sprayed on the surface of the airborne fibers as they exit the fiberizer. When the binder-coated fibers adhere to the conveyor in the forming chamber they form a matrix that, after drying, can be shaped and cut. Most fiber products have either binder or oil or both, although some specialty products are made without either. The amount of binder used is also expressed as the percent by weight of the total bulk fiber product. For this study, binder was grouped into two levels, "with binder" and "without binder" (Table I). Binder ranged from 4.5% to 13.8% binder with a mean of 8.4%. Krantz et al.[3] did not find a strong effect of binder on airborne fiber size during the processing of bulk samples of European rockwool. In general, however, U.S. glass fiber products tend to have a higher percentage of binder than European products. We hypothesized that the effect of binder would be similar to that of oil, that is, the use of binder would increase the GM(D) of the airborne fiber.

Field distinguished air samples were collected within 5 ft of a fiber generating source ("near field") from those collected at greater than 15 ft from such a source ("far field") (Table II). To have a clear distinction between the near and far fields, no samples collected between 5 and 15 ft from a fiber source were used for this investigation. Schneider et al.[2] proposed that the GM(D) of airborne fiber size distributions are likely to decrease with time and distance from the fiber source largely due to sedimentation and ventilation; we hypothesized the same.

Handling of the bulk fiber products was grouped into three categories based on the amount of mechanical energy they required (Table II). Air samples collected in the fiber forming areas where very little direct handling of the fiber product occurs were classified as "low mechanical energy input." Where fiber product was manipulated but not cut or abraded, air samples were classified as "moderate mechanical energy input." This group contained the most common types of handling in the MMVF production industry, such as rolling the fiber mat as it comes off the production line, folding and stacking building insulation batts, and baling or bagging blowing wool. The "high mechanical energy input" group included air samples collected during the processing of fiber product with power equipment that cut or chopped the fiber mats with saw-toothed blades or ground the surface of fiber products. Currently, these high energy tasks are performed automatically, although workers may be in close proximity. In the past, these activities were done by hand. There is no clear documentation regarding whether the majority of fibers that become airborne during the processing of an MMVF product are actually formed during the fiberizing stage and held in the fiber matrix until they are disrupted, or whether the aerosolizable fibers are created by the finishing processes. Because it is difficult to break glass fibers longitudinally,[28] we hypothesized that the handling processes would not effect the fiber size proportions.

Fiberizer type distinguished those fibers made by rotary spinners, which use wheel-shaped disks with holes in them to spin fibers from molten glass, from those made by flame attenuation, which uses forced air to blow fibers from a stream of molten glass (Table II). It was thought that, because of its greater turbulence, the flame attenuation process could be associated with an airborne fiber diameter and length distribution that had more variability than the rotary spinner process and that this increased variability would increase the HAF1 proportion.

Facing is the application of a material such as paper or foil over one or both sides of a fiber mat. The mats were either "all faced;" "mixed faced," in which case the product was made both with and without facing material; or "none faced" (Table II). It was hypothesized that facing would have no effect on the fiber size proportions.

Study Design and Air Sampling Strategy

A strategy was developed to collect air samples for each level of the seven product and process factors. To find all possible combinations, it was necessary to conduct air sampling in eight MMVF production factories. These factories were located throughout the United States and were among the oldest and largest. The factories are described in detail elsewhere.[21,22] Sixty air samples were collected with at least two air samples for each unique combination of factors, although some product and process combinations did not exist, for example, the grinding of microfiber products. Fixed location, area samples were collected instead of personal samples to permit evaluation of specific product and process factors, rather than the estimation of an individual worker's exposure.[29,30] Sampling was performed at production lines and in work areas that were isolated from other production processes so that the airborne fibers could be associated with the processing of a particular bulk product.

Air Sample Analysis, Construction of the Total Bivariate Size Distributions, and Calculation of the Fiber Size Proportions

A total, bivariate (diameter and length) fiber size distribution was constructed from each air sample using more intensive analyses than required by standard PCOM methods such as the NIOSH Method 7400.[9] Fibers were counted and sized using electron microscopy according to the WHO/EURO Reference Scheme[31] with an additional requirement: rather than tallying fibers in diameter and length categories, individual fiber diameters and lengths were recorded. Depending on the fiber dimensions, scanning electron microscopy (SEM) or transmission electron microscopy (TEM) was used to perform fiber counting and sizing so that a distribution of all fiber dimensions could be constructed. At least 100 particles with an aspect ratio of three or greater were counted and sized from each air sample. Standard PCOM methods typically count far fewer fibers. The fiber sample size was chosen based on simulations conducted by Schneider[32] showing that the expected deviations between the estimated and true GM and GSD for a sample of 100 fibers are approximately 10%. More than 6600 fibers were counted and sized from the 60 air samples. The number of fibers meeting the size criteria for the two fiber indices representing the NIOSH Method 7400 B and the HAF1 were divided by the number in the total, bivariate fiber size distribution to obtain the fiber size proportions, p_B and p_{H1}.

Statistical Analyses

Analysis of variance (ANOVA) and analysis of covariance (ANCOVA) models with fixed effects were fit using the general linear models (GLM) procedure of SAS (SAS Institute Inc.). The models were unbalanced because, as noted above, some combinations of production process factors did not exist. Because air samples with a greater number of fibers contributed more information to the analyses, each air sample was weighted by the inverse of its variance $(1/p(1-p)/n)$. The final models were then used to predict the proportions, p_{H1} and p_B, for typical values of the model parameters.

For both proportions, the predictors were considered in all one-way and two-way models, with their interactions. No models with four or more terms (main effects and interactions) yielded stable parameter estimates, likely due to collinearity among the independent variables. The final models were ones in which parameter estimates for the independent variables were statistically significant at $p < 0.05$. Whenever an interaction term was added, the main effects variables were left in the model regardless of level of statistical significance. When more than one model had statistically significant predictive explanatory variables, the model with the most precise coefficients and the highest R^2 value was selected.

RESULTS

Fiber Size Proportions

Table III shows the values of p_{H1} and p_B along with the five parameters of the bivariate lognormal distributions, all calculated directly from the raw air sampling data. For simplicity of presentation, the 60 airborne fiber samples are pooled by nominal diameter and use of oil, two product and process factors identified as strong determinants of airborne fiber size (see below). The results show that as the nominal diameter of the bulk product increased, the GM(D) of the total airborne fiber size distribution tended to increase; likewise, the proportions of fibers falling into both p_{H1} and p_B tended to increase. These relationships differed, however, for the airborne fibers associated with the use of oil as compared to those with no oil. This finding is explained further in the modeling section of the results and in the discussion.

Table III results also show that p_{H1} and p_B vary considerably across the 60 fiber samples. For p_{H1} the range is 0.07 to 0.68; for p_B, the range is 0.06 to 0.95. This indicates that the two indices differ in these air samples depending on the production factors. Of particular note is that the ratio of p_{H1} to p_B varies both in magnitude and direction, from 0.40 to 2.21. This finding indicates that one proportion is not simply a subset of the other, nor do the proportions vary by a simple relationship across the full range of MMVF products.

TABLE III. Sixty Airborne Fiber Samples Pooled by Nominal Diameter and Oil Use

Nominal Diameter	Oil Use	Number of Fibers	GM(D) (μm)	GSD(D)	GM(L) (μm)	GSD(L)	τ(DL)	p_{H1}	p_B	p_{H1}/p_B
0.7	No	705	0.11	1.86	3.15	2.90	0.31	0.07	0.06	1.24
1.0	No	450	0.18	2.66	4.40	2.66	0.32	0.11	0.16	0.70
2.2	Yes	349	1.05	2.09	17.77	2.18	0.01	0.38	0.76	0.50
3.0	No	314	0.16	2.23	4.18	2.99	0.31	0.10	0.12	2.21
3.5	Yes	336	2.35	1.93	36.05	1.98	0.28	0.62	0.55	1.14
4.2	Yes	1417	1.53	2.08	23.44	2.08	0.24	0.48	0.73	0.67
4.5	Yes	422	1.81	2.04	30.79	1.86	0.38	0.55	0.69	0.84
4.7	Yes	676	1.10	1.78	19.73	1.65	0.24	0.42	0.87	0.54
5.5	No	214	1.47	1.82	12.17	2.33	0.36	0.30	0.60	0.50
5.6	Yes	868	0.88	1.94	16.09	1.79	0.28	0.33	0.84	0.40
5.7	No	243	1.22	1.91	26.67	2.14	−0.04	0.52	0.95	0.54
6.1	No	237	1.76	1.81	24.35	1.81	0.18	0.50	0.79	0.64
6.2	Yes	380	1.58	1.83	21.78	2.02	0.25	0.46	0.80	0.58

Note: The five parameters of the bivariate lognormal fiber size distributions, the proportions of fibers meeting the HAF1 and NIOSH Method 7400 B rules size criteria, and the ratio of the HAF1 and NIOSH 7400 B rules proportions are shown for the pooled fibers.

The Proportion Models

As measured by the significance of one-way ANOVA models, the associations of both p_{H1} and p_B with each product and process factor were generally strong (Table IV). One-way models with all factors but field had significant overall F-statistics ($p < 0.01$). Nominal diameter was the strongest predictive factor for both p_{H1} and p_B.

In the two- and three-way models, handling, fiberizer type, and facing, were correlated with nominal diameter. For example, certain nominal diameters tended to be made by a particular fiberizer type. Once nominal diameter was in a model, these factors were no longer significant. Both oil and binder, in contrast, remained important predictors of p_{H1} and p_B along with nominal diameter. Two-way interaction terms significantly improved the fit of these models.

The best fitting models for both p_{H1} and p_B were two-way models with nominal diameter as a continuous variable, oil as a categorical variable, and an interaction term (Table V). The structure of these models for both proportions, p_{H1} and p_B, was:

$$\hat{y} = \beta_0 + \beta_1(\text{ND}) + \beta_2(\text{Oil}) + \beta_3(\text{ND})(\text{Oil}) \qquad \textbf{(2)}$$

where

$\hat{y}$ = dependent variable, either p_{H1} or p_B
β_0 = intercept
β_1 = parameter estimate for nominal diameter (ND)
β_2 = parameter estimate for oil; oil = 0 if "with oil" (the level used as the comparison)
oil = 1 if "without oil"
β_3 = parameter estimate for ND × oil interaction term

The p_{H1} and p_B models with nominal diameter and binder did not fit quite as well as the models with nominal diameter and oil, based on comparisons of R^2 and the precision of the model coefficients. The best fitting p_{H1} model using nominal diameter and binder was:

$$p_{H1} = 0.0006 + 0.09(\text{ND}) + 0.06(\text{Binder}) - 0.02(\text{ND})(\text{Binder}) \qquad \textbf{(3)}$$

where Binder = 0 if no binder was present, and Binder = 1 if binder was present. The best fitting p_B model using nominal diameter and binder was:

$$p_B = 0.01 + 0.05(\text{ND}) + 0.12(\text{Binder}) + 0.10(\text{ND})(\text{Binder}) \qquad \textbf{(4)}$$

TABLE IV. Values of HAF1 and NIOSH B Rules Proportions from One-Way Models for Each Process and Product Factor

Process/Product Factor	N	Observed Mean HAF1 Proportion	SE	R^{2A}	Observed Mean B Rules Proportion	SE	R^{2A}
Nominal diameter				0.68^B			0.81^B
Microfiber	12	0.09	0.03		0.10	0.08	
Fine	9	0.37	0.23		0.48	0.30	
Medium	39	0.44	0.10		0.78	0.14	
Oil				0.64^B			0.68^B
With oil	39	0.45	0.11		0.76	0.14	
Without oil	21	0.19	0.17		0.30	0.33	
Binder				0.29^B			0.43^B
With binder	45	0.39	0.15		0.70	0.25	
Without binder	15	0.25	0.23		0.31	0.32	
Field				<.001			<.001
Near	49	0.36	0.18		0.61	0.32	
Far	11	0.34	0.19		0.55	0.30	
Handling				0.18^B			0.23
Low handling	9	0.31	0.20		0.61	0.42	
Moderate energy	34	0.33	0.20		0.51	0.32	
High energy	17	0.43	0.10		0.79	0.14	
Fiberizer type				0.28^B			0.23^B
Rotary spinner	36	0.42	0.15		0.69	0.21	
Flame attenuation	24	0.26	0.19		0.47	0.39	
Facing				0.27^B			0.17
All faced	18	0.41	0.14		0.70	0.22	
Mixed faced	7	0.50	0.10		0.69	0.13	
None faced	35	0.30	0.19		0.53	0.37	

Note: SE = Standard error.
[A]Fraction of the variance in HAF1 and B Rules proportion explained by the factor in a one-way analysis of variance model.
[B]Overall model F statistically significant ($p < 0.05$).

TABLE V. Empirical Models for Prediction of the Proportions of MMVF in Two Aerosol Size Fractions Based on Nominal Diameter and Use of Oil

		Model Coefficients^A (Standard Error) p-Value				Predicted Values of the Mean Proportions^B Using the Final ANCOVA Model (No. of Samples)					
						Without Oil Nominal Diameter			With Oil Nominal Diameter		
Dependent Variable	R^2	Intercept	Nominal Diameter (ND)	Oil	ND × Oil Interaction	Micro	Fine	Medium	Micro	Fine	Medium
HAF1 Proportion (p_{H1})	0.82	+0.60 (0.08) <0.001	−0.03 (0.02) 0.06	−0.59 (0.08) <0.001	+0.10 (0.02) <0.001	0.07 (12)	0.21 (3)	0.36 (6)	0.57^C (0)	0.51 (6)	0.45 (33)
NIOSH 7400 B Rules Proportion (P_B)	0.86	+0.69 (0.19) <0.001	+0.04 (0.04) 0.34	−0.82 (0.02) <0.001	+0.11 (0.04) 0.009	0.002 (12)	0.30 (3)	0.62 (6)	0.73^C (0)	0.81 (6)	0.89 (33)

^{A}Coefficients from the model (Equation 2 in text): $\hat{y} = \beta_0 + \beta_1(\text{ND}) + \beta_2(\text{Oil}) + \beta_3(\text{ND})(\text{Oil})$.
^{B}Proportions = the fraction of the total number of fibers in an air sample that meet the size criteria for the HAF1 index or the NIOSH Method 7400 B rules (see text).
^{C}Caution is advised in using this value. It represents extrapolation beyond the observed data.

The final HAF1 proportion model (Table V) explains the variability in p_{H1} quite well ($R^2 = 0.82$). The mean values of the nominal diameters, grouped into three categories typically used in industry, were used to calculate predicted values of p_{H1} (Table V). In the fiber samples with oil, p_{H1} decreased slightly as nominal diameter increased. In contrast, in the fiber samples without oil, p_{H1} increased rather sharply as nominal diameter increased. This can be seen in Figure 1, where the observed values of p_{H1} for all 60 fiber samples are shown along with the model's predictions for p_{H1} with and without oil. Ninety-five percent confidence bounds placed on each point made the figure difficult to read. As a compromise, error bars were placed on representative points falling at different locations on the best fit lines. The error bars are shown for a range of proportions.

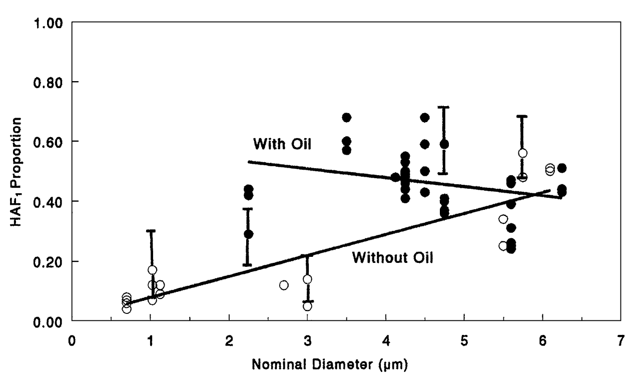

FIGURE 1. Relationship between fiber nominal diameter and the HAF_1 proportion for sixty airborne fiber samples. The observed proportions from fiber samples with oil are shown by closed circles, and those without oil by open circles. The lines represent the best fitting model of this relationship. Representative 95% confidence bounds for the observed proportions are shown (see text).

In the model for p_{H1}, the interaction term for nominal diameter and oil was highly significant ($p < 0.001$, Table V), indicating that the effect of oil differs by nominal diameter. The greatest effect of oil was seen in microfibers where oil increased the p_{H1} eight-fold ($p_{H1} = 0.07$ for microfiber without oil and 0.57 for microfiber with oil). For fine fiber, oil increased the p_{H1} more than twofold, while for medium nominal diameter fiber, oil had little effect on p_{H1}.

The NIOSH Method 7400 B rules proportion model (Table V) explained the variability in p_B very well ($R^2 = 0.86$). Using this model, the predicted mean p_B for a microfiber without oil was quite small (0.002). This reflects the fact that the NIOSH Method 7400 B rules, which uses PCOM, does not count fibers having diameters less than approximately 0.25 μm and lengths less than 5 μm. Thus, although this method is commonly called the "respirable" fiber method, it counts only a small proportion of the airborne fibers with diameters likely to deposit in the alveolar region. As was the case with p_{H1}, the greatest effect of oil was on the microfibers. The p_B was increased about three-fold for fine fibers with oil and about 1.4 times the medium nominal diameter fibers with oil as compared with the fine and medium fibers without oil. Also, as with p_{H1}, p_B increased sharply as nominal diameter increased for fibers without oil. However, p_B does not vary much across nominal diameter groups for fibers with oil (see Figure 2; as in Figure 1, confidence bounds are given for representative points).

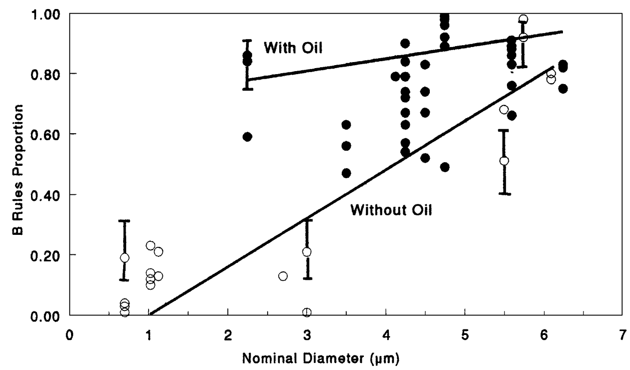

FIGURE 2. Relationship between fiber nominal diameter and the NIOSH 7400 Method B Rules proportion for 60 airborne fiber samples. The observed proportions from fiber samples with oil are shown by closed circles, and those without oil by open circles. The lines represent the best fitting model of this relationship. Representative 95% confidence bounds for the observed proportions are shown (see text).

DISCUSSION AND APPLICATION

Prediction of the Fiber Size Proportions

The results support the hypothesis that fiber size can be predicted using routinely collected production process information. A significant amount of the variation in the fiber size proportions ($R^2 = 0.82$ for p_{H1}, $R^2 = 0.86$ for p_B) can be explained by two process factors: the nominal diameter of the bulk product, and whether oil was applied.

A limitation of this study is that it was based on only 60 air samples. However, these were used in a more efficient design than most studies of the determinants of exposure. The dependent variable can be estimated more precisely when there is an even distribution of air sampling measurements over the levels of factors.[29]

The models presented here may be generalizable to other fiber glass production facilities because the data were collected in eight factories with a wide range of general plant environmental factors. The models can be used to calculate a predicted value of p_{H1} and p_B for the airborne fiber exposure generated during the processing of glass wool bulk product with any nominal diameter, with or without oil, as long as the nominal diameter or amount of oil used does not vary greatly from those used to develop the model.

A limitation of the models is that they were developed from air monitoring data that were collected over a period of several months. We do not know how stable the airborne fiber size distributions are over many years. Fortunately, a large portion of the variation in the proportions (>80%) is explained by only two factors, which historical U.S. MMVF industry records indicate have not changed greatly over time. The stability of the fiber size distributions over time would probably be a more important issue if the variability in the size distributions were determined by factors that were known to have changed over time, such as the configuration of a workroom.

The Effects of Individual Product and Process Factors

While the main purpose of this study was research, the findings regarding individual production factors are relevant for professional practice because they can be used to develop interventions to improve the work environment.[33] For example, the finding that nominal diameter was such a strong predictor of airborne fiber size, while the factors related to the handling of the bulk product were not, suggests that fibers in the size ranges that can become airborne are created during fiberizing rather than during the finishing processes. Thus, interventions to change the airborne fiber size distributions should be aimed at fiber forming.

Oil

The p_{H1} decreases while p_B increases with increasing nominal diameter when oil is used; however, the change in either direction is slight compared with the increase in p_{H1} and p_B across nominal diameter products without oil (Figures 1 and 2). Thus, the use of oil has a dampening effect across the range of fiber sizes investigated here. A possible explanation is that oil tends to reduce the proportion and absolute number of smaller diameter fibers that become airborne, perhaps by adhering small fibers to larger ones or to the bulk material. Oil appears to have somewhat less of an effect on the larger diameter fibers. Such an oil effect would reduce the proportion of small diameter fibers that become airborne, thus increasing the proportion (but not number) of larger diameter fibers in any given air sample. However, it is not recommended that oil be used in place of engineering controls to reduce the number of small fibers; oil itself can be a respiratory hazard.

Binder, Field, Handling, Fiberizer Type, and Facing

Of the factors other than nominal diameter and oil, only binder had a significant effect on the proportions once nominal diameter was in the models. It was hypothesized that binder would have an effect on the proportions similar to that of oil and this appears to be the case, although the effect is not as strong. Also consistent with our prior hypotheses were the findings that handling and facing did not have an effect on the proportions. Contrary to our prior hypotheses, near vs. far field did not appear to have an effect on the proportions nor did fiberizer type. A possible explanation for the lack of a field effect is that the airborne fibers were too small to settle rapidly, and/or the settled fibers were rapidly re-entrained due to air turbulence. Thus, moving away from a fiber source (at least up to 15 ft) is not likely to reduce exposure to small diameter fibers.

Application in Exposure Assessment Research

In the air monitoring data evaluated here, there are significant differences in the magnitude and even the direction of the ratio of the proportions across the various airborne fiber size distributions (Table III). The widely variable ratio of p_{H1} to p_B suggests that members of an epidemiologic study cohort having exposure assignments based on standard PCOM methods, such as NIOSH Method 7400, could be misclassified if a biologically based index, such as the HAF1, is more closely related to the disease outcome of interest.[7] Therefore, adjustment of historical PCOM fibrous aerosol monitoring data for use in epidemiology may be warranted.

The widely variable ratio of p_{H1} to p_B also suggests that the proportion of fibers meeting the NIOSH Method 7400 B rules criteria cannot be adjusted to the proportion of fibers meeting the HAF1 criteria using a single multiplier for all airborne fiber size distributions. However, the ratio of two fiber size proportions such as p_{H1} and p_B can be used to adjust a standard fiber concentration measurement to the concentration of fibers in a different range of its size distribution: $p_{H1}/p_B \times$ NIOSH Method 7400 B Rules concentration (C_B) = HAF1 concentration (C_{H1}). An example follows using the nominal diameter and use of oil regression models to predict p_{H1} and p_B and then multiplying the NIOSH Method 7400 B rules concentration determined from an actual air sample (0.20 fibers/cm^3) by the p_{H1}/p_B ratio. The air sample was collected during the processing of a glass wool product made without oil and having a nominal diameter of 3 μm.

Determination of a predicted value for the HAF1 proportion using the model from Table V:

$$\hat{p}_{H1} = 0.60 + (-0.03)(3) + (-0.59)(1) + (0.10)(3)(1) = 0.22$$

Determination of a predicted value for the NIOSH Method 7400 B rules proportion using the model from Table V:

$$\hat{p}_B = 0.69 + (0.04)(3) + (-0.82)(1) + (0.11)(3)(1) = 0.32$$

Adjustment of NIOSH Method 7400 B rules concentration to the HAF1 concentration:

$$C_{H1} = \frac{0.22}{0.32} \times 0.20 \text{ f/cm}^3 = 0.14 \text{ f/cm}^3 \quad \textbf{(5)}$$

This HAF1 concentration of 0.14 fibers f/cm^3 is a measure of the airborne concentration of fibers in a new size fraction. It has the same units as a fiber concentration measurement made using standard methods, so it can be used in the same manner and compared with the fiber exposure estimates used in previous epidemiologic studies. In using the model to predict fiber concentrations in different size fractions, a measure of the variability of the predicted size proportions could be calculated. These fractions are linear combinations of model parameters, each with a measure of variance and covariance. For any combination of nominal diameter and oil use, an estimate of the variance of the predicted size fraction could be generated using the model parameters and the variance-covariance matrix. Monte Carlo methods are well suited for this.

The modeling approach developed here could also be used to adjust a standard fiber concentration measurement to the concentration of fibers meeting the other previously proposed, biologically based fiber size indices.[7,11–18] To do so would require that models be constructed of the proportions of fibers meeting the size criteria of these indices. The adjusted concentrations could then be used to estimate the biologically relevant airborne fiber exposure for a member of a study cohort so that the exposure-response association could be assessed in an epidemiologic study.

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